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Public Participation in Plant-Pollinator Conservation: Key Assessment Areas that Support Networked Restoration and Monitoring

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Public Participation in Plant-Pollinator Conservation:

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by

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Abstract

Environmental problems are growing at a pace and scale that traditional research methods alone can no longer tackle. Innovative research models that utilize contributory, participatory and crowdsourcing methods are rapidly emerging to fill this gap. For these participatory efforts to be effective and sustainable, however, closer attention must be paid to key components that can promote coordinated action and sustainability. Through the lens of public participation in plant-pollinator conservation, I have, with rigorous social-ecological inquiry, offered three foundational assessment areas that can provide scientific support to this nascent field: accuracy, ecological significance and scalability.

In the first study (Chapter 2), I explored a common concern about citizen science – that a lack of foundational knowledge, or familiarity with following scientific protocols could lead to inaccurate data collection. I evaluated the accuracy of plant phenology observations collected by citizen scientist volunteers following protocols designed by the USA National Phenology Network (USA-NPN). Phenology observations made by volunteers receiving several hours of formal training were compared to those collected independently by a professional ecologist. Approximately 11,000 observations were recorded by 28 volunteers over the course of one field season. Volunteers consistently identified phenophases correctly (91% overall and 70% during transitions) for the 19 species observed. Accuracy varied significantly by phenophase and species ($p<0.0001$). Volunteers who submitted fewer observations over the period of study did not exhibit a higher error rate than those who submitted more total observations, suggesting that volunteers with limited training and experience can provide reliable observations when following explicit, standardized protocols. Overall, these findings demonstrate the

legitimacy of phenology observations collected by volunteers, an important finding for the increasing number of analysts relying on data collected by citizen scientists.

In Chapter 3, I explored a common concern that restoration efforts implemented by the public may not have adequate ecological value. I addressed key ecological variables to determine how small-scale patches attracted pollinators and explored which of these variables might be best to prioritize for restoration efforts suited to public initiatives. This study demonstrated that in small-scale plant restoration sites, plant diversity and resource (nectar) availability significantly affects the abundance and diversity of pollinating insects. Specifically, the treatments which contained high-resource (nectar-rich) plant species increased pollinator abundance and diversity the most. Plant diversity increased pollinator diversity and abundance only in the absence of high-resource plants. Pollination facilitation was observed in high resource treatments, but varied among species. Competition for pollinators was observed in high diversity treatments but did not affect seed set for high-resource plants in any of the treatments. Together, these results suggest that managers or landowners who are restoring patches of native plants as habitat for pollinators should prioritize including species with high nectar production, and secondarily, a diverse mix of species if space and resources allow.

In Chapter 4, I explored an emergent approach to public participation in regional community science initiatives (and networks) through an exploratory case study of the New York Phenology Project. I demonstrated that local organizations have the opportunity to utilize existing data aggregation platforms to activate regional collaborative alliances to achieve what is often challenging for large–scale contributory projects. I describe our hands-on experience of conceiving and launching a regional

network and outline a model that could serve as a guide for catalyzing networks. Drawing on direct experience and interviews with network partners, I developed a description of key categories related to network node success, and a linked assessment tool that could be used to evaluate network node capacity and project outcomes. The assessment tool will be used to test preliminary findings in a more formal quantitative and qualitative exploration in future studies.

In Chapter 5, I explored an exceptional long-term, community-level phenology dataset that spans New York State, USA (1802-2017), and found interesting and significant patterns of phenological change over time. The dataset provides statewide phenology and temperature data that extend further back in time than any previously known dataset for the region, extending to years prior to or at the beginning of recent human-caused global warming. I found that most species are flowering and leafing earlier in recent years (2009-2017) than they did in the early 19th century (1802-1861). Plants are flowering 11 days earlier and leafing 18.8 days earlier—with some species flowering up to 27 days earlier and leafing up to 31 days earlier over that time period. Most of this change was driven by warming mean spring temperatures (MST) over that time; mean spring temperatures warmed by 1.0°C statewide (2.5°C in New York City) on average between the historical and contemporary periods. Seasonality, Life Form, and the interaction between Seasonality and Life Form explained variation in phenology among species. The large number of geographically distinct sites in this dataset permitted novel investigation into differential changes in phenology between urban and rural areas (urban areas have more advanced phenology than their rural counterparts) and between insect and wind pollinated trees by seasonal category (insect pollinated trees are showing more

advanced phenology than wind pollinated trees in both early and late spring). This analysis has brought the efforts of a historical network into a modern context and has illustrated how organized long-term monitoring efforts can be valuable for ecological discovery.

This combined work provides a diverse contribution to the field of public participation in monitoring and conservation efforts. While thorough and disciplined ecological theories drive the design of the research, I simultaneously strove to help meet the ongoing demand for useable, purposeful insights into how to support public efforts to restore plant-pollinator habitats, monitor key ecological dynamics such as phenology, and scale networks capable of collecting data that address issues of global change.

Dedication: To all of those who in the past volunteered in service of us today, to all of those who volunteer today in service of the future - you have given your precious time to gather data and create habitat in hopes of a more just and sustainable world for all living creatures. We see you. Your contributions make a difference.

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Table of Contents

List of Tables

List of Figures

Chapter 1.

Introduction:

Public participation is expanding the frontiers of science and conservation at a breathtaking pace. Threats from global change are driving individuals and organizations to mobilize on behalf of scalable initiatives and the advancement of mobile and database technologies and networks are accelerating the potential for orchestrated action (De Coster et al. 2015, Sequeira et al. 2014, Thorson et al. 2014). Generating ecologically significant data for policy decision-making, land management, and even crisis preparedness necessitates scale; observations of a wide array of interacting species, collected across large geographic regions. Environmental problems often exert their influences at scales that traditional research methods can no longer tackle (Bonney et al. 2014, Heidorn 2008, Wolkovich et al. 2012). New research models that utilize contributory, participatory and crowdsourcing methods are rapidly emerging to fill this gap (Schwartz et al. 2017).

The surge in public participation in various stages of scientific research, most commonly referred to as "citizen science' is a global movement and is being deployed in many fields, including human health, astronomy, air quality monitoring, and ecology (Greenwood 2007, Ingwell & Preisser 2010, Kremen et al. 2011). In an era of diminishing funding and burgeoning needs, the scientific community often has neither the resources nor the infrastructure to gather comprehensive data without significant assistance. These public-professional collaborations are mutually beneficial: scientists gain access to vast amounts of additional data while citizen scientists improve their scientific literacy, increase their knowledge of natural history and biology, even develop

better scientific and critical thinking skills (Brossard et al. 2005, Silvertown 2009, Trumbull et al. 2000). Citizen science deployment in large-scale ecological projects was, and to an extent still is, largely contributory, with citizens acting as "sensors" collecting data for a scientist-led project (Dickinson et al. 2012).

New horizons for citizen science

As citizen science projects proliferate and grow more ambitious, however, there is a greater opportunity for contributory citizen science projects to become more collaborative and ambitious. Research could be co-developed between scientists, partner organizations and participants; iterative feedback loops of information between stake-holders and intentional optimization of participant engagement and community development can lead to more revealing outcomes (Dickinson & Bonney 2012, Fitzpatrick 2012, Lawson et al. 2017). Communities of observers increasingly include a range of scientists, non-scientists, students, teachers, staff, religious groups and more. The work that follows does not attempt to create new (or argue existing) typologies of participation models, but in order to represent the various communities of observers working within various participation models, we will use the term "community science" interchangeably with public participation in science research (PPSR) and citizen science. As this field itself is rapidly evolving, definitions, models and typologies that characterize the field are evolving as well (Cooper et al. 2007, Shirk et al. 2012, Wiggins et al. 2011, Wilderman 2007). The current language is inconsistent and imprecise, but the movement is real and underway nonetheless.

Community science is one of many progressive, socially inspired meta-trends

currently emerging in ecology. The evolution of community science projects is already leading to regional and national networks of activity and formal network development. For example, the USA-National Phenology Network has grown exponentially over the past 10 years. This monitoring program started out with protocols for backyard observers - and due mainly to requests for increased functionality of the observation platform coming directly from observers themselves - is now comprised of hundreds of organized local projects, some of which are housed within major regional networks who collectively submit millions of observations yearly. The global project iNaturalist has also grown to include over 750,000 observers and over 7 million observations in the last ten years. These examples highlight the opportunity that large-scale data aggregation platforms offer to both scientific and non-scientific partners to coordinate and scale networks of activity around key environmental issues.

Public participation in plant-pollinator conservation

One conservation area currently exploring community science research models is the field of plant-pollinator conservation. The public increasingly understands that the decoupling of plant-pollinator mutualisms is potentially disastrous and that changes in spatial and temporal connectivity for plant and pollinators across landscapes could compromise overall ecosystem functioning, food security and economics (Henning & Ghazoul 2011, Memmott et al. 2007, Vanbergen et al. 2013). Pollinator gardens, phenology monitoring programs, and a vast array of volunteer monitoring initiatives devoted to tracking plants and pollinators are examples of widespread action related to plant-pollinator research and habitat restoration. The combination of these initiatives is a

potential game-changer for the plant-pollinator conservation movement and the interplay between data collection and restoration creates opportunities for adaptive management at large geographic scales (Cooper et al. 2007). Through these initiatives, individuals and communities have the opportunity to contribute meaningful data to ascertain how plants and animals are responding to global change at a regional, continental, or global scale. However, scaling-up from individual patches to increase connectivity across managed landscapes will require coordinated effort and detailed analyses (Goddard et al. 2010). Many interesting ecological questions can be addressed if cooperative and robust long-term monitoring and implementation initiatives are successful, especially if knowledge gains can be used to feedback on restoration efforts.

The role of networks in restoration and monitoring

What if, for example, connected patches across landscapes could facilitate climate-change resilient gene flow from the urban core (already experiencing high temperatures and CO_2 levels) to surrounding reserve areas and beyond? What if pollinator resource patches could be designed with such intention that any balcony in a city could contribute to connectivity and conservation? What if phenology-monitoring networks could track timing and population variations across species and landscapes with such precision that conservation funding for target species could be allocated efficiently? These types of questions can only be addressed through coordinated approaches to restoration and research that involve networks of action and monitoring. What if these networks could ultimately be self-sustaining and replicable across broad geographic regions? Ultimately, before we undertake the monumental efforts required to

launch and sustain these types of networks, we must first address foundational questions about whether these conservation and monitoring efforts are as impactful as we believe them to be. How do we assess the very core suppositions of ecological value? How do we effectively apply established ecological theory in these implementation and research efforts? How, when moving from ecological theory to practice, do we insure that all stakeholders are actively engaged in the iterative, collaborative process of developing solutions?

Key assessment areas that support networked initiatives

There is a wealth of empirical evidence still needed to adequately support the efforts of this nascent movement at local, regional scales and beyond. Ecologically rigorous assessments are vital to the projects themselves and to the sustainability of the collaborations among the diverse suite of stakeholders involved in this movement. In this dissertation, I have explored key assessment areas that I believe to be of paramount importance to the next steps in the evolution of this dynamic conservation field. My goal has been to bring the rigor of ecological analysis to the growing interdisciplinary field of public participation in scientific research - in service of building community-level capacity for conservation, monitoring and habitat restoration for plants and pollinators. Empirical, evidence based studies in three key assessment areas – accuracy, ecological significance and scalability, demonstrate how science can actively support effective public participation in plant-pollinator conservation. The figure and text below describe three assessment areas I consider to be essential to some of the most emergent public activity areas in plant-pollinator conservation (phenology monitoring and pollinator

habitat implementation) but are also highly relevant to successful public participation in science research initiatives across disciplines (Figure 1.1).

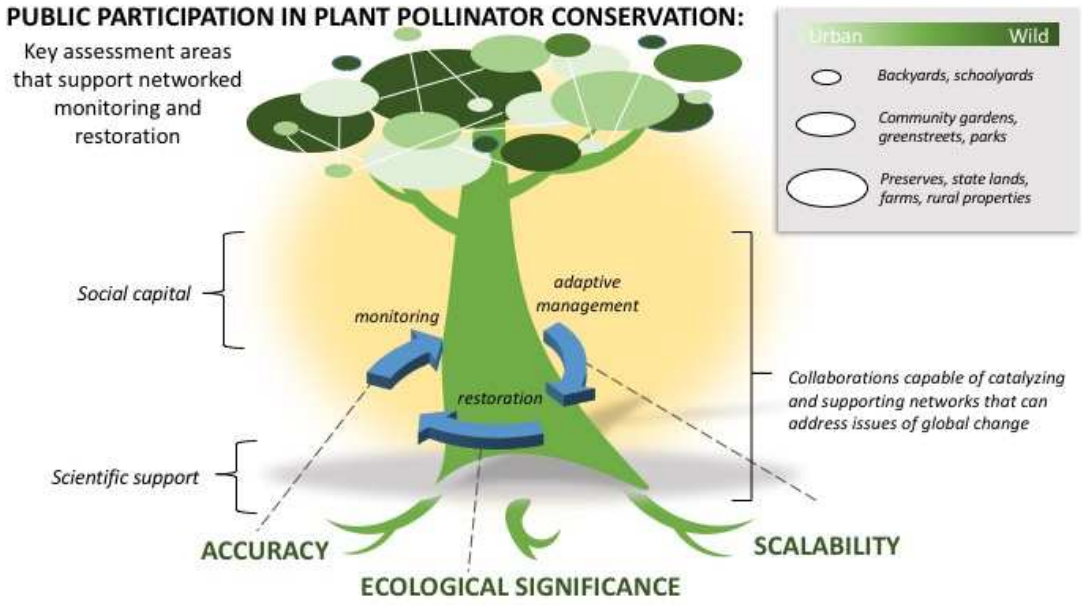


Figure 1.1. Three key assessment areas relevant to public participation in plant-pollinator conservation and community science research initiatives across disciplines.

Protocols used for community science monitoring efforts must be evaluated to ascertain that they are appropriate for non-professionals with limited training, and that the data yielded are accurate. Many studies have demonstrated that citizen scientists and other volunteer participants can often collect observations of sufficient quality that they can be used in scientific discovery and management decisions (Courter et al. 2012, Haklay 2010). Examples include: citizen scientists identifying advances in the egg-laying dates of migratory birds (Dunn & Winkler 1999), re-discovering a ladybug species thought to have gone extinct (Losey et al. 2007), and monitoring species declines, as shown by the Reef Environmental Education Foundation, which used scuba

divers to conduct more than 83,000 surveys recording declines in 14 shark species over a 15-year period (Ward-Page et al. 2010). However, despite the volume of evidence supporting citizen science data quality, accuracy is not a given and does not always translate across projects and scales. The involvement of individuals with varying levels of experience or knowledge could create concerns about data validity (Foster-Smith & Evans 2003, Hunter et al. 2013). For example, some studies have shown that particular tasks such as species level identification for certain groups of organisms (e.g. plants or insects) are not always suited for non-professionals without extensive taxonomic training (Kremen et al. 2011, MacKenzie et al. 2017).

Before major resources are deployed to launch or scale any major efforts, the data collection protocols must be evaluated and found to be amenable to community scientists. In the realm of plant-pollinator conservation, temporal connectivity (phenological synchronization) across landscapes is a research area that has not been adequately studied. To address this large-scale research area using community-science based research methods, accuracy must first be validated at smaller scales, such as whether standard plant phenology protocols are amenable to volunteer data collection. Therefore, Chapter 2 explores whether citizen scientists can collect plant phenological data of sufficient quality to be useful for scientific purposes. This study was the first to assess citizen-science accuracy of the plant phenology monitoring protocols for the largest phenological data collection effort in the United States (the USA-National Phenology Network monitoring program). Results from this effort supported general accuracy for citizen-scientist collected phenology data and led to protocol revision and refinement for specific aspects of the national phenology monitoring program.

Projects being developed and implemented that aim to support large-scale conservation goals must have evidence-based ecological significance in order to adequately meet those goals. Public engagement in restoration and monitoring require different levels of pre-assessment than engagement focused solely on environmental education and nature appreciation. There is a significant difference between developing public awareness and issuing action-based directives. For example, conservation initiatives meant to restore populations of organisms that have not been properly vetted can be ineffective, or worse, have unintended consequences - such as detrimental effects on other threatened species or habitats (Chauvenet et al. 2011, Liu et al. 2007). In the realm of plant-pollinator conservation, there are a multitude of implementation efforts managed by a diverse suite of stake-holders. These efforts may be able to create high-quality habitat if design is adequately informed by ecological research.

However, pollinator gardens or patch plantings are often implemented by private residents, through schools, or municipalities and conservation advocacy organizations and generally do not involve formal evaluation of either the techniques used to create the habitat or the resultant ecological impact. For example, "pollinator friendly" seed mixes are often used to create pollinator gardens. A recent study found that many of these mixes contain non-native species (some considered weedy or aggressive) as well as closely–related species with a high potential to negatively impact remnant native species through genetic swamping or low-quality pollination via heterospecifc pollen transfer (Johnson et al. 2017). This example illustrates the potential impact of using a planting technique that might be "easy" for the public to implement (a seed packet), without prior evaluation of the possible effects of the technique.

Additionally, the motivations of the individuals participating in programs intended to have measureable landscape or systems impact must be considered in order to engender long-term commitment. People are often participating because they believe (or can see) that their efforts are making a significant ecological difference (Bramston et al. 2011, Bruyere & Rappe 2007). An initiative that does not have measurable success factors that participants can witness first-hand can potentially engender a future reluctance to be involved in any efforts on behalf of the environment.

As managed landscapes continue to proliferate, identifying and creating high-quality habitats will be key to any strategy to conserve and restore pollinators (Baldock et al. 2015). Strategic design of habitats at the local scale could potentially have profound effects on the diversity of pollination interactions at the landscape scale (Sabatino et al. 2010). Many of the staple recommendations for how to plant and support diverse and abundant pollinator populations and increase connectivity between patches in urban, residential and rural landscapes have not been properly assessed. In Chapter 3, I carried out a traditional ecological field experiment to examine key ecological dynamics relevant to pollinator patch planting, namely; how key plant traits and patch diversity affect diversity and abundance of pollinators and the subsequent effects these interactions have on seed set via facilitation and competition for floral resources. From an applied perspective, species composition and plant diversity affect patch quality, and patch quality affects how pollinators forage and ultimately how pollinator populations are supported. Facilitation and competition are both important factors to how patches support pollinator populations, but also to how plant reproductive success is affected by pollinator visitation. This study is the first I am aware of that controls for patch size,

thereby isolating the effects of diversity (from functional diversity and environmental conditions) on pollinator diversity and abundance. Though the questions and hypotheses were designed to test ecological theory, the results are intended to directly inform planting design in small patches across urban, residential and rural landscapes to support both pollinator and native plant populations. In addition, the protocols used to evaluate the pollinator habitat patches were designed to be adoptable by community-science projects and other research efforts that may not involve trained ecologists.

Finally, an evaluation of whether or not a project can in fact be replicated and scaled - in a way that the ecological value of the data justifies the effort – is required to efficiently utilize limited resources. Any launched ecological citizen science initiative aimed at restoration and environmental decision-making or action likely presupposes ecological significance. Once certain of the data accuracy (and the next level of ecological significance it points to), however, we must evaluate what it will take to sustain and extend the work of the initiative. Scale in community science does not simply mean growth. Scale describes growth that rapidly outstrips any need for significant resources to support it. Community science, for example, has the potential to scale without significant resource investment because self-motivated individuals elect to participate for non-financial reasons such as: developing a sense of belonging, caretaking the environment, and expanding personal learning (Bramston et al. 2011).

While a project's ability to scale is dependent on many factors (i.e. ease of use and adoption, a clear value proposition for participants and the ability to generate robust datasets that can be analyzed by scientists or other data-end users), the macrostructural properties of the organizations launching community science programs and strategies for

achieving successful scale in both national and regional contexts are too often under-evaluated (Wiggins & Crowston 2011). Case studies that demonstrate successfully scaled networks can provide critical information to a growing movement of public participation in conservation. I describe core learnings on network scalability in Chapter 4 of this work, essentially a descriptive case-study focused on my experience launching and managing the community science-based New York Phenology Project. The New York Phenology project rapidly scaled from one site to over 30 sites in less than 5 years and is currently one of the top data contributing regional phenology networks in the country. I outline the steps I took to conceive, launch and scale this regional project in a way that can be applied to both national and local organizations seeking to activate regional community science networks. I also report on insights gained (through hands-on experience and interviews with members of the network) to describe the organizational attributes and capacities that appear most foundational to network node success. I describe key categories of inquiry and an assessment tool that can aid in future analyses designed to assess and support community science networks.

Chapter five of this work is a culmination of the three assessment areas I have outlined and described above. This study compares two phenological datasets collected by networks of observers across two centuries, (a historic network collecting data from 1802-1878 and the contemporary New York Phenology Project network launched in 2012) to determine the effects of climate change on common plant species found in the Northeast. The 150 historic and modern locations allow for a spread of sites across a fairly large geographic region with a range of highly urbanized sites to very rural sites. The combined dataset has among the oldest known phenology data in North America

and is one of the only known examples of a multi-site comparison of ground-collected historic and modern phenology data. I highlight species, and groups of species, that are responding most (and least) to changes in climate and whether variation among phenology is related to seasonality, life form, urban-rural classification or pollination syndrome. While this chapter is focused on the scientific results and ecological significance of this phenological comparison, the effort was only possible because the networks themselves were launched, scaled and sustained. The data used in this study are considered valid because citizen science collected phenology data was determined to be accurate enough for scientific use (as evidenced by our Chapter 2). Therefore, chapter 5 is an example of the impact that public participation in ecology can achieve when supported by rigorous science.

An experiential and translational approach to traditional ecological inquiry

This interdisciplinary dissertation begins to assess key areas where science can fundamentally support the burgeoning field of public participation in plant-pollinator conservation by evaluating data accuracy, ecological significance and scalability of plant-pollinator monitoring and conservation techniques in the urban-wild context. While thorough and disciplined ecological theories drive the design of the research (described in the chapters below), a primary goal of this dissertation is to simultaneously help meet the ongoing demand for useable, purposeful insights into how to develop healthy plant-pollinator habitats and monitoring projects.

The approach of making ecological principles relevant to non-ecological stakeholders and deepening our understanding of the ways ecologists can collaborate with a wider array of stakeholders (on an issue relevant to global environmental health

and sustainability) aligns with the core principles of the emerging field of translational ecology. Central to the work of translational ecologists is the prioritization of collaboration, engagement, commitment, communication, process and decision-framing, which necessitates the rigorous practice of bringing additional (often unexpected) stakeholders into the ecological dialogue (Wall et al. 2017). In the process of implementing these research efforts, we entered into collaborations, dialogues and innovative inquiries that have launched a long-term body of research and applied work in the fields of theoretical, experimental and applied ecology. The work of this dissertation was impossible without this multi-disciplined, translational approach administered in collaboration, transparency and generative dialogue. These qualities form the very backbone of translational ecology (Schwartz et al. 2017). I will further examine my learnings on the relevance of the principles of translational ecology to this body of work in the Conclusion.

[1]Chapter 2.

Assessing accuracy in citizen science-based plant phenology monitoring

Introduction

The number of studies that have documented changes in plant and animal life cycle events, or phenology, in response to a warming climate continues to grow (Cleland et al. 2007, Thackeray et al. 2010, Walther et al. 2002). Not all species are responding in the same ways; some species are advancing their timing of spring development, others are delaying, and still others have not shown obvious change (Parmesan and Yohe 2003, Root et al. 2003). Disproportionate deviations in phenology among interacting species can lead to changes in plant and animal community composition, structure, and functioning. The decoupling of species interactions, such as between plants and pollinators or animals and their food sources, has been reported in many systems (Both et al. 2009, Edwards and Richardson 2004, Memmott et al. 2007, Pearce-Higgins et al. 2005, Winder and Schindler 2004). However, due to the nature of available data, most of these changes have been documented in local studies or are narrowly focused on a handful of species (Wolkovich et al. 2012). The ability to ascertain how plants and animals are responding to climate change at a regional, continental, or global scale necessitates observations collected across the geographic region on the same species, following standardized protocols. Engaging volunteers in various stages of scientific research, broadly referred to as "citizen science," has been employed in a wide range of

[1] Fuccillo KK, Crimmins TM, de Rivera CE, Elder TS. (2015) Accessing accuracy in citizen science-based phenology monitoring. International Journal of Biometeorology. 59 (7): 917-926

fields, including astronomy, air quality, and biology (Dickinson et al. 2010, Greenwood 2007, Ingwell & Preisser 2010, Kremen et al. 2010, Tregidgo et al. in press). Citizen science opportunities have been shown to offer benefits to participants such as improved scientific literacy, increases in knowledge about natural history and biology, and increased scientific and critical thinking (Brossard et al. 2005, Cooper et al. 2007, Dickinson et al. 2010, Trumbull et al. 2000). Moreover, many studies have demonstrated that citizen scientists and other volunteer participants can collect observations of sufficient quality that they can be used in scientific discovery and management decisions (Bell 2007, Boudreau and Yan 2004, Cooper 2013, Courter et al. 2012, Galloway et al. 2006, Haklay 2010, Lovell et al. 2009, Sparks et al. 2008). Citizen scientists, however, may struggle with more complex measurements such as abundance and frequency of occurrence of specific species or groups (Fore et al. 2001, Galloway et al. 2006, Gardiner et al. 2012, Kremen et al. 2011, Nerbonne & Vondracek 2003) or may introduce bias by collecting observations on weekends more than weekdays (Cooper 2013, Courter et al. 2012, Sparks et al. 2008). Studies that evaluate the specific conditions that yield the highest quality of citizen-collected data can serve to increase confidence in the resulting datasets.

Phenology observation programs exist in many countries as a means of documenting plant and animal response to climate. Many of these programs engage citizen scientists in creating and submitting reports in an attempt to amass observations at the scales and densities necessary to support rigorous research (Koch 2010). Programs such as FrogWatch USA (www.frogwatch.org), eBird (www.ebird.org), and Project BudBurst (www.budburst.org) collect, store, and share observations of plant or animal

phenology collected by citizen scientists. One such program, *Nature's Notebook* (www.nn.usanpn.org), managed by the USA National Phenology Network (USA-NPN), currently engages thousands of scientists and volunteers in documenting phenological stages across the country. To date, little work has been done to evaluate whether citizen scientist volunteers, such as the ones who participate in *Nature's Notebook*, can yield accurate assessments of plant phenological status.

Over the course of a season, plants progress in and out of various phenological stages, called *phenophases*, such as leaf-out, flowering, and fruiting, which may overlap temporally and are evaluated independently by the observer (Figure 1). Transitions in and out of phenophases (the transitions from a phenophase not being present to being present and vice-versa) are critical events to pinpoint accurately, as changes in phenophase onset and end have been indicative of plant response to changing climate conditions in numerous studies (e.g., Menzel et al. 2006, Parmesan and Yohe 2003, Thackeray et al. 2010). We hypothesized that volunteer observers may perform best at accurately identifying various phenophase conditions during the period between onset and end, and may struggle more with correctly identifying phenophase status during periods of transition, either at the onset or end of a phenophase, as the defining characteristics can be diminutive during these times.

Quantifying volunteers' ability to accurately assess phenophase status, as well as the situations in which they tend to perform better or worse at assessing status, can increase confidence in the millions of phenology observations that have been collected by phenology monitoring programs across the country. Our primary aim was to quantify the accuracy with which citizen scientist volunteers can assess phenological status in

plants. Our secondary aim was to assess the variation in accuracy among species, phenophases and number of observations reported in order to generate preliminary recommendations for plant phenology protocol refinement and identify areas for future studies. In this study, we evaluated the abilities of participants who received several hours of formal training, and therefore are most representative of those yielded by the hundreds of observers participating in *Nature's Notebook* via a local organization with leadership. However, because individuals who participate in *Nature's Notebook* independently also must spend a similar amount of time in self-study in order to participate, the findings may also extend to the thousands of participants who submit observations independently. Our questions were: (1) How accurately were trained observers able to assess plant leaf, flower, and fruit phenophases overall? (2) Did volunteers' accuracy in identifying phenophase status vary by species, plant functional group or phenophase? (3) Did volunteers' ability to accurately identify phenophase status decrease during periods of phenophase transition? (4) Did volunteers who submitted more observations over the period of study exhibit a lower error rate than those who submitted fewer total observations?

Materials and methods

Study design

In fall of 2010, a "phenology trail" was established in Forest Park, a large urban reserve in Portland, Oregon. Three replicates of nineteen plant species, which are listed in Table 1, were marked with an identification sign along the edge of an existing trail. Species spanned three plant functional groups (tree, shrub, forb) and were selected based

on their ease of identification and proximity to the trail. To recruit participants to this evaluation study, we advertised this volunteer opportunity via Portland State University and Portland Parks and Recreation listservs, contacted local organizations such as Portland Audubon, talked with curious trail users while installing the phenology trail and posted informative signs at the beginning of the trail. Twenty-eight participants were drafted. Participants' backgrounds ranged from outdoor enthusiast to environmental science students, though none had experience in collecting phenology observations and none reported any notable expertise or background in botany. The project leader (KKF), a trained plant ecologist, comprehensively studied the protocols and resources on the USA-NPN project website before the season began and was in frequent contact with the organization over the course of the season.

In March 2011, volunteers attended a six-hour training led by the project leader. This training included an introductory presentation on plant phenology (~1 hr), an introduction to the USA-NPN website, how to sign up and what resources are available (~1.5 hrs), an orientation to recording data using datasheets and plant species identification practice online (~1 hr), and hands-on phenophase identification in the field (~1.5 hrs). Approximately 1 hour was spent getting to the field site and having a social lunch. Over the course of the field season, the project leader offered a few opportunities for additional informal in-person training and also provided email-based support. There were only a few instances of participants seeking further in-person training or clarification on phenophase identification via email. The project leader provided phenophase photographs for several species as available but received no confirmation of whether participants used them or not. Additionally, some volunteers had contact with

one another by email and in person to a limited extent over the course of the season. The plant phenology protocols used in this study were a slightly modified version of those offered through the USA-NPN phenology observing program, *Nature's Notebook*, in 2010 (ver0.2; www.usanpn.org/results/nndocumentation).

We requested that participants report, for each individual plant, the status of five phenophases, "emerging leaves," "unfolded leaves," "open flower," "full flower," and "ripe fruits" (Table 2). On each visit, observers reported "yes" (the phenophase was observed), "no" (the phenophase was not observed), or "?" (the observer looked but could not evaluate whether the phenophase was present or not) for each of the phenophases for each of the 57 individual plants. A copy of the datasheet used by the observers appears in the Supplementary Information. Volunteers were encouraged to make observations at least once a week. The project leader made observations using identical protocols on the same individual plants once a week along the marked phenology trail. Observations were collected for 16 weeks: April 1 to June 16, 2011.

Data analysis

Volunteers in this study participated as their schedules allowed, and did not always collect observations on the same day as the expert. To minimize the chance that differences between a volunteer and the expert in phenophase status reported could be due to the plant under investigation undergoing a change in phenophase status between the two observation dates, we restricted the observations collected by volunteers to those collected within two days of the expert (before or after). We also removed all records pertaining to the "emerging leaf" and "unfolded leaf" phenophases after onset was

ascertained from the expert's records because, at the time of this study, the USA-NPN protocols did not clearly specify when to stop recording "yes" when the emerging leaf and unfolded leaf phenophases ended. These exclusions resulted in the removal of 623 observations.

To obtain overall accuracy, we tracked the nature of all disagreements between volunteers and the expert observer, for example, if the expert said yes while the volunteer indicated no (false negative) or if the expert said no and the volunteer indicated yes (false positive). These nominal accuracy values were used in subsequent statistical tests. To account for the variation in the total number of observations submitted by each volunteer, we calculated overall accuracy in assessing phenophase status by first calculating the accuracy for each individual and then averaging across these measurements.

We calculated each observer's accuracy (percent of total observations that were in agreement with the expert) by species and by phenophase. We then used a two-way repeated measures analysis of variance (ANOVA) test to evaluate whether observers' ability to identify phenophase status correctly varied by species or phenophase. We tested for main effects and interaction between the two terms. As data were percents, we transformed the data using the arcsin transformation to achieve the required test distribution. Because species and plant functional types are not independent, we tested for differences among observers' accuracy by plant functional type in a separate one-way ANOVA.

To evaluate whether volunteers' abilities to correctly identify phenophases decreased during times of phenophase transition, we limited the dataset to records that

were associated with times of transition. We identified distinct phenophase transitions for each individual plant using the project leader's observations. Shifts from one phenophase state ("yes" or "no") to the other were determined to be a transition when the phenophase status was reported as the same state for at least two consecutive weeks prior to the shift, and then as the alternate state for the next two consecutive weeks. We identified 59 clear "no to yes" phenophase transitions and 44 clear "yes to no" phenophase transitions within the project leader's dataset. We then extracted all volunteers' observations for the same individual plants for the same weeks, and classified them as correct if the observer noted the transition occurring in the same consecutive period as the project leader, or incorrect if their reports did not agree with the project leader. We calculated transitional accuracy by observer, and then averaged across observers' accuracy values to determine an overall average accuracy.

To evaluate whether accuracy was greater for volunteers who logged more observations over the course of the season, we implemented linear regression and tested for a relationship between the total number of observations logged by each volunteer and the percent of correctly identified phenophases. Both "number of observations" and "percent correctly identified phenophases" were transformed using a log+1 transformation. We repeated this comparison for phenophase transitions only, to evaluate whether volunteers' abilities to correctly identify phenophase transitions increased with experience observing transitions. "Number of transition observations" was transformed using a log+1 transformation. All statistical analyses were conducted using JMP version 9.0.

Results

The project leader collected 2,903 unique observations of plant phenophase status over the course of the season. The 28 volunteer participants collected over 11,000 observations within two days of the project leader's observations (average observations collected per volunteer: 395.6 ± 606.1 [mean±SD; range: 30-2,954; median: 212]). Volunteers correctly identified phenophases 91.3% (±4.6%) of the time (Table 3). The most common type of error was a false negative, where the project leader noted a phenophase as occurring ("yes") and the volunteer recorded it as not occurring ("no"). False negatives occurred approximately 4% of the time and typically were recorded at the beginning of a phenophase. Volunteers and the project leader marked "uncertain" at approximately the same rate (Table 3).

The main effect of species was significant ($F_{9,1483}$=10.50, p<.0001), as was the main effect of phenophase ($F_{3,\ 1483}$=43.46, p<.0001). The interaction of these two factors was also significant ($F_{63,1483}$= 6.19, p<.0001), indicating that the percentage of phenophase reports that were in agreement with the project leader varied significantly by species and phenophase (Figure 2). The main effect of plant functional type across all phenophases was not significant ($F_{2,73}$=1.64, p=0.20). The phenophases accurately identified most frequently were "ripe fruits" (99.3% correct, Figure 2, Table 4) and "unfolded leaves" (95.6% correct). "Emerging leaves" exhibited the greatest rate of incorrect reports (81.3% correct), among all functional groups. Errors among the "open flowers" phenophases were primarily false negatives. Disagreements between the project leader and the volunteer participants for the "full flower" phenophase mainly

involved either the project leader or the volunteer indicating uncertainty ("?") regarding the phenophase status. Within phenophases, volunteers' performance at assessing accuracy varied noticeably among species (Figure 2).

Project participants collected 352 observations of phenophase transition (average transitional observations collected per volunteer: 14.3 ± 22.5 [mean±SD; range: 1-95; median: 7]). As hypothesized, volunteers' ability to correctly identify phenophase status dropped during periods of phenophase transitions. Note that results for transitional accuracy may be overly conservative, as some transitions may have occurred within the two-day span between when the volunteer and the expert observed the phenophase. Average accuracy (across all phenophase transitions, all species) was 70.2%±21.0%.. Volunteers performed much better at accurately identifying the end of a phenophase (91.9±14.8% accurate, when averaged across all "yes to no" transitions) than the onset (63.6±26.1% accurate, when averaged across all "no to yes" transitions). For phenophase onset transitions ("no to yes"), volunteers performed best at accurately identifying the initiation of "unfolded leaves" (Table 4). Among the two flower phenophases, volunteers performed better at accurately identifying onset of "full flowers," (Table 4, Figure 3). Regarding phenophase end transitions ("yes to no"), volunteers performed very well at accurately identifying transitions for "open flowers" and "full flower," and struggled with pinpointing the end of "ripe fruits" (Table 4, Figure 3b).

We did not detect a statistically significant relationship between the total number of observations volunteers logged and the percent of correctly identified phenophases

(r^2=0.04; p=0.34, Figure 4a). There was a similarly non-significant relationship between the number of phenophase transition observations volunteers logged and the percent of correctly identified phenophase transitions (r^2=0.003; p=0.76, Figure 4b).

Discussion

In this study, volunteer participants lacking previous experience with evaluating plant phenology correctly identified phenophases across a variety of plant functional groups greater than 91% of the time. Our findings suggest that even in their first season of participating in a program such as *Nature's Notebook*, volunteers can provide reliable observations of plant phenology when following explicit, standardized protocols. Beaubien and Hamann (2011) observed a similar pattern among participants in the Alberta PlantWatch program, a plant phenology observation program based in Canada: participants who had been with the program for greater than ten years performed only slightly better at accurately identifying species and phenophases than new participants. Similarly, new participants' observations were "largely unbiased" and nearly as temporally precise as the long-term observers (Beaubien & Hamann 2011).

Volunteer participants have performed comparably well in other citizen science projects similarly focused on visually differentiating among a limited number of choices, such as gender of individuals or shades of color of coral (Delaney et al. 2008, Siebeck et al. 2006). A strength of phenology monitoring in general may be that participants are asked the equivalent of multiple choice questions, with possible responses including "yes," "no," and "unknown," as opposed to other citizen science projects where participants are asked to answer the equivalent of open-ended questions, such as

cataloging biodiversity at a site or classifying species. (Bell 2003, Foster-Smith and Evans 2003, Kremen et al. 2011, Lovell et al. 2009, Nerbonne and Vondracek 2003).

Participants' performance was lowest when assessing changes in phenophase status; volunteers pinpointed transitions with 70% accuracy. Recognizing leaves, flowers, and fruits when they barely meet the criteria for a report of "yes" status requires extra careful observation and concentration. We expect that observers' ability to accurately identify transitions at their true onset and end could improve in subsequent seasons, especially if they receive feedback about their success rates at transitions and tips on how to notice these. Increases in observer accuracy with experience have been reported in several studies of citizen science programs of bird and biodiversity monitoring, where reports require high skill (e.g., Bas et al. 2008, Jiguet 2009, Schmeller et al. 2009). Improvements in those studies were attributed to increased familiarity with protocols, improved identification skills, and improved species location skills. Recognizing the subtle changes that plants undergo at the initiation of periods of transition may similarly require higher skill that is garnered through experience.

The estimates of transitional accuracy calculated from this study may be overly conservative. Because volunteers' observations were not always collected on the same day that the expert collected observations, there is the potential for transitions to have occurred in the one or two-day window that in some cases occurred between observations. In a situation where a transition did occur, and the observations collected on either side of this transition reflected the plant status correctly, the transition would have been marked as being assessed incorrectly. The volunteers may have performed better at assessing transitions than our data reflect; this could be better assessed in future

studies where observers and volunteers collect data on the same day, and ideally, at the same time.

Though the findings of this study suggest that volunteers' abilities to correctly identify phenophase status at transitions did not improve substantially with experience recording phenophases. Our study was confined to a single season, and transitions into and out of a particular phenophase were not viewed repeatedly for a specific species within the study duration. We hypothesize that volunteer observers abilities to correctly identify phenophase transitions would improve in subsequent years, when they would be viewing transitions that they had observed previously.

Variations in accuracy among functional groups, phenophases, and species

Volunteers' performance in accurately assessing phenophase status varied among species and phenophases. The differences in participants' abilities to correctly assess phenophase status may be attributed to several factors. First, participants for whom the species and phenophases are new, as those in this study, inherently become more familiar and comfortable with recognizing them over the course of the season. Among our participants, false negatives were the most common form of error, where observers marked "no" when the project leader reported the phenophase as occurring. This may suggest that newly trained participants, unpracticed at fine-scale phenophase discernment, may not acknowledge a phenophase as occurring until it has reached a more obvious state than when an expert may identify it as occurring. As training and observations in this study began at the start of spring, the higher rate of correct assessments in reporting the end of phenophases compared to reports of onset may be

evidence of this phenomenon. We reason that after participants have watched a particular phenophase progress over the course of a season, they are more familiar with what they are seeing, and are more able to identify the end with accuracy. The project leader notes that volunteers who observe the same species the following season would likely do better at assessing phenophase onset due to increased familiarity with the plant itself, knowing what to expect and what to look for.

Secondly, variations in volunteers' abilities to correctly identify phenophase status are also a function of conditions specific to certain species and functional groups. For example, the comparatively low accuracy seen in "unfolded leaves" reports for trees can be explained by the fact that for most of these individual trees, the canopies were many meters overhead. Volunteers needed binoculars to assess leaf status most accurately, and in many instances, binoculars were forgotten and phenophases could not be evaluated for minute detail. In contrast, fruit phenophases were assessed accurately at a very high rate. This is likely due to the absence of fruits over most of the study. On the majority of dates that participants made observations, no fruits were present, and the large number of instances where both observers and the project leader documented "no" resulted in a high rate of agreement for this phenophase. In addition, some flowers and fruits were very difficult to see. As an example, false negatives occurred relatively frequently in reports of *Vaccinium parviflorum* (VAPA). *V. parviflorum* flowers are easy to miss—they are pale green in color, quite small, and frequently only observed from a vantage point below the shrub, requiring observers to manipulate branches to see the flowers. The higher rate of false negatives for this plant could be attributed to participants not going to these lengths to look for the flowers. For emerging leaves, the

lowest accuracy tended to be among the forb species. One reason for this could be that emerging leaves for forbs are often under leaves or detritus early in the season and some volunteers may not have moved them aside, or could not tell the newly emerging species apart.

A third explanation for variation in volunteers' ability to correctly identify phenophase status among species and phenophases, is the ambiguity that was present in some of the phenophase descriptions used in this study. The protocols and phenophases implemented in this study were early iterations of the USA-NPN plant protocols, and did not yet have species-specific descriptions for how to evaluate status. Further, some species' protocols included unfitting phenophases that have since been removed. For example, participants were asked to report the status of "full flower" (at least half of the flowers open) for *Trillium ovatum* (TROV), which produces a single flower in a season. This phenophase caused confusion among some observers, as they were unsure whether a single open bloom met the criteria for "full flower" for this species. Finally, the version of the protocols used in this study required that participants observe the structure under investigation, such as emerging leaf tips, flowers, or fruits, on at least three locations on the plant. Cases may have occurred where the project leader observed three instances of the phenophase under consideration, and therefore reported "yes," and volunteers also observed the event as occurring, but only detected one or two instances, and therefore reported "no.". Each of these confusing or problematic aspects to the observation protocols has been addressed in recent updates to the USA-NPN protocols.

Recommendations and implications for future research

In general, trained volunteer performed well at evaluating plant phenophase status. The decrease in transitional accuracy and the fine scale variation in species and phenophase accuracy however, should be considered judiciously by data users. Though the number of observations per species in this study alone cannot lead to any definitive conclusions about which species and phenophases are most appropriate for continued phenology monitoring, we have some general preliminary suggestions for phenology monitoring programs and/or end users of phenology data. Our results suggest that phenophase transition onset should be evaluated by data users with a higher level of scrutiny, particularly for the following species/phenophase combinations: emerging leaves for forbs, emerging leaves for large trees (when canopy is far overhead), and open flowers for large trees and for any species that have inconspicuous flowers. In this study, observers generally performed better at evaluating "unfolded leaves" (now called "leaves") among leaf phenophases and "open flowers" among flower phenophases. The decreased accuracy during transition times could be mitigated by increased training and resource materials (such as photographs or more detailed descriptions) for species-specific phenophase transitions.

Our recommendations aided USA-NPN in the refinement of their protocol in the following ways: assessment of full flower as a phenophase was eliminated, (and "intensity" of phenophase was added so that observers could enter numerical assessments of phenophases), more detailed explanations as to when to stop reporting a phenophase as occurring were added to the protocols, particular characteristics to look

for per species were added to the protocols and only one instance of phenophase occurrence (instead of three) is now required for positive identification.

The participants in this study best represented individuals that participate in *Nature's Notebook* through an established group or organization such as a Master Gardener chapter, nature center, or National Wildlife Refuge, which represent 17.2% of all active *Nature's Notebook* participants and approximately 30% of all submitted observations (Crimmins et al., unpublished data). However, because individuals that participate in *Nature's Notebook* directly must spend some time familiarizing themselves with the program and protocols, this time spent self-training (via online resources such as PowerPoint presentations, webinars, photographs and dialogue with USA-NPN staff) may be close to what individuals that participate via a group are provided. Therefore, the findings of this study may extend to individuals that participate directly in *Nature's Notebook* without formal in-person training as well as other phenology monitoring programs such as Project Budburst which use similar phenology monitoring protocols and training resources with their groups and individual participants. Evaluations of specific programs and models are needed however to provide evidence for this assertion.

One limitation of the present study is the assumption that the project leader, to whom all of the volunteer participants' observations were compared as an assessment of their performance, always judged phenophases correctly. Indeed, the project leader indicated some concerns in her ability to always correctly interpret and apply some of the phenophase descriptions, particularly regarding the end of "open flowers" and "full flower." This may have resulted in a higher error rate. Future studies that assess

volunteers' abilities to accurately assess phenophase status could be improved in several ways. First, if at all possible, the volunteers and the "expert" should collect observations on the same day. Second, multiple experts should collect observations, to minimize errors resulting from the expert assessing phenophase incorrectly. Third, we recommend repeating the study over multiple field seasons, as this would enable a determination of whether volunteers' abilities to accurately identify transitions improve with experience. It could also be valuable to collect demographic and background information, to determine whether volunteers' backgrounds can predict their accuracy at assessing phenophase status.

Ideally, studies such as this one should be repeated using the most current and rigorously tested phenology monitoring protocols for a wider array of species, to further ensure that the protocols can yield high-quality, reliable phenology data by citizen scientists receiving limited training and follow-up support. Based on this study, phenology monitoring programs have great potential to yield high quality data usable by scientists and resource managers. Determining the conditions upon which these monitoring programs are the most successful will allow for increased validation of these broad-scale data sets capable of answering pressing ecological questions about global change.

Chapter 2. Tables and Figures:

Table 2.1. Plant species included in the Forest Park phenology trail project. N=3 replicate plants for each of the 19 species.

Species	Abbreviation	Functional group
Acer circinatum (vine maple)	ACCI	tree
Acer macrophyllum (big leaf maple)	ACMA	tree
Achlys triphylla (vanilla leaf)	ACTR	forb
Corylus cornuta (hazelnut)	COCO	tree
Disporum hookeri (Hooker's fairybells)	DIHO	forb
Hydrophyllum tenuipes (Pacific waterleaf)	HYTE	forb
Oelmeria cerasiformis (Indian plum)	OECE	tree
Rubus parviflorus (thimbleberry)	RUPA	shrub
Rubus spectabilis (salmonberry)	RUSP	shrub
Rubus ursinus (native blackberry)	RUUR	shrub
Smilicina racemosa (false Soloman's seal)	SMRA	forb
Symphorocarpus albus (snowberry)	SYAL	shrub
Tellima grandiflora (fringe cup)	TEGR	forb
Tiarella trifoliata (foamflower)	TITR	forb
Tolmia menziesii (piggy-back plant)	TOME	forb
Trillium ovatum (trillium)	TROV	forb
Vaccinium parviflorum (red huckleberry)	VAPA	shrub
Vancouveria hexandra (inside-out flower)	VAHE	forb
Viola glabella (stream violet)	VIGL	forb

Table 2.2. Phenophase definitions used for the 19 plant species observed in the Forest Park phenology study.

Phenophase	Definition
Emerging leaves	The green tip of an emerging leaf is just visible on three buds, but not yet unfolded to expose the leaf base (petiole).
Unfolded leaves	The petiole, or leaf base, is visible on three leaves. The first leaves have pushed themselves outside of the bud. You may need to carefully bend the leaf backwards to observe this.
Open flowers	Three open, fresh flowers are visible, showing their reproductive parts.
Full flowers	At least half (50%) of the flowers are open and fresh.
Ripe fruits	Three fruits show the coloring characteristic for their variety and can be removed easily from the fruiting lateral.

Table 2.3. Possible combinations and frequency of plant phenology status reported for the same individual plant on the same date by an expert and a volunteer participant in the Forest Park phenology study.

Expert report	Volunteer report	Classification	Frequency
Both report Y, N, or ?		Agreement	91.7%
Y	N	False negative (Type II error)	3.0%
N	Y	False positive (Type I error)	1.7%
Y	?	Volunteer uncertain	1.4%
N	?	Volunteer uncertain	1.2%
?	N	Expert uncertain	0.8%
?	Y	Expert uncertain	0.2%

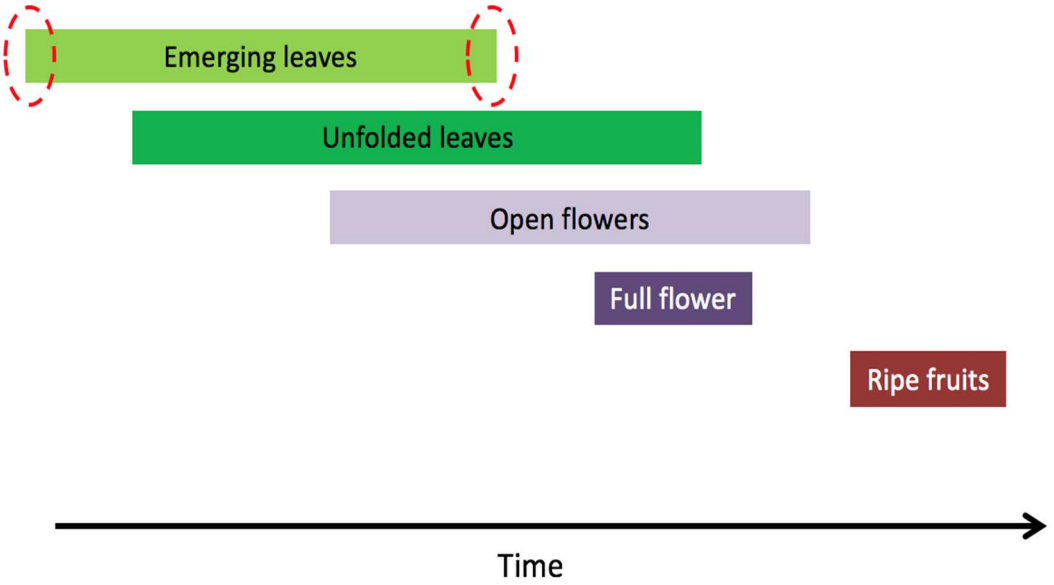


Figure 2.1. Conceptual model of plant phenophase timing over the course of a season Phenophase transitions occur at the onset and end of a phenophase, highlighted for "emerging leaves" at the tail of the phenophase duration.

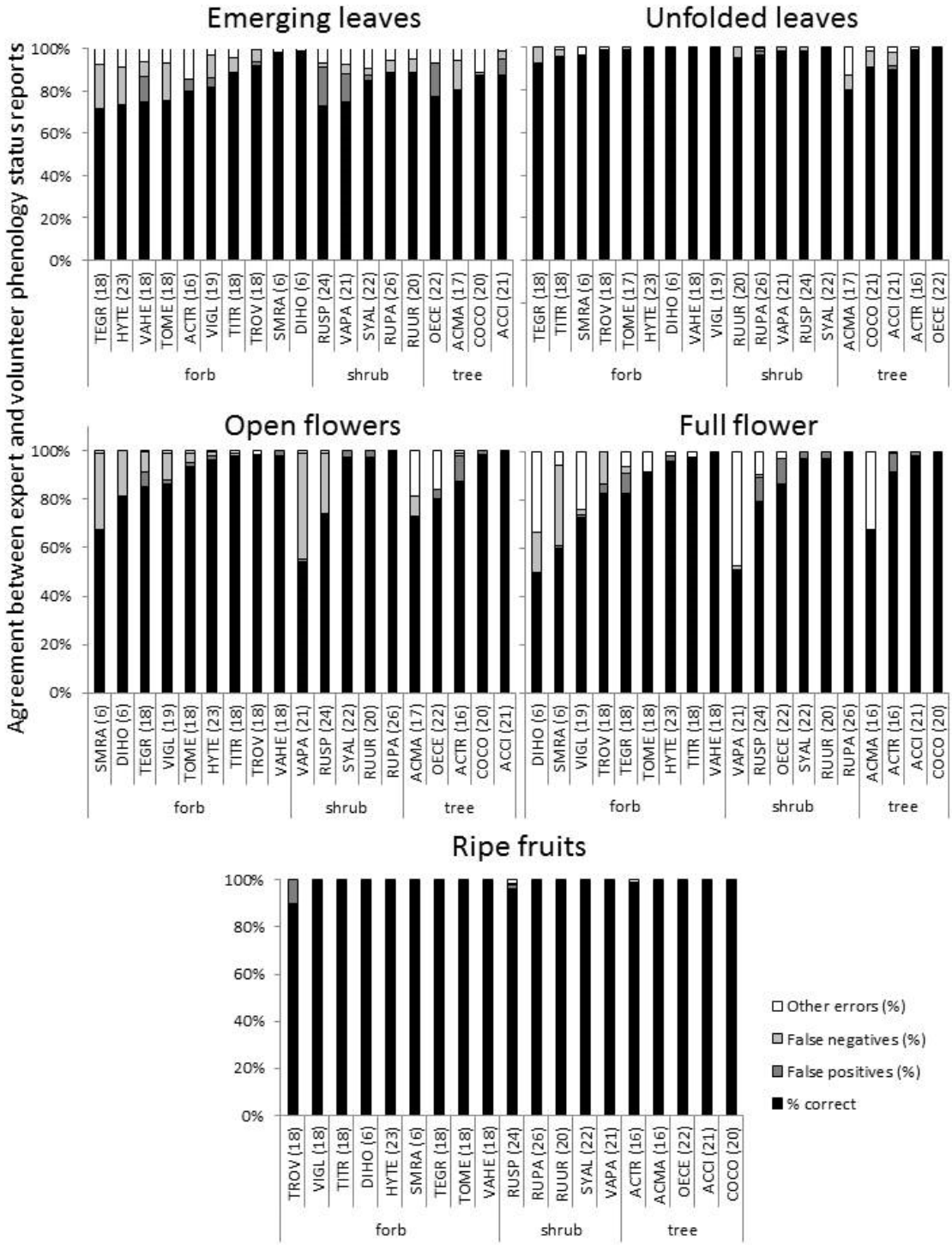


Figure 2.2. Stacked bar graphs of plant phenology status as reported by an expert and volunteer participants in the Forest Park phenology study. Results are grouped by plant phenophase and plant functional group.

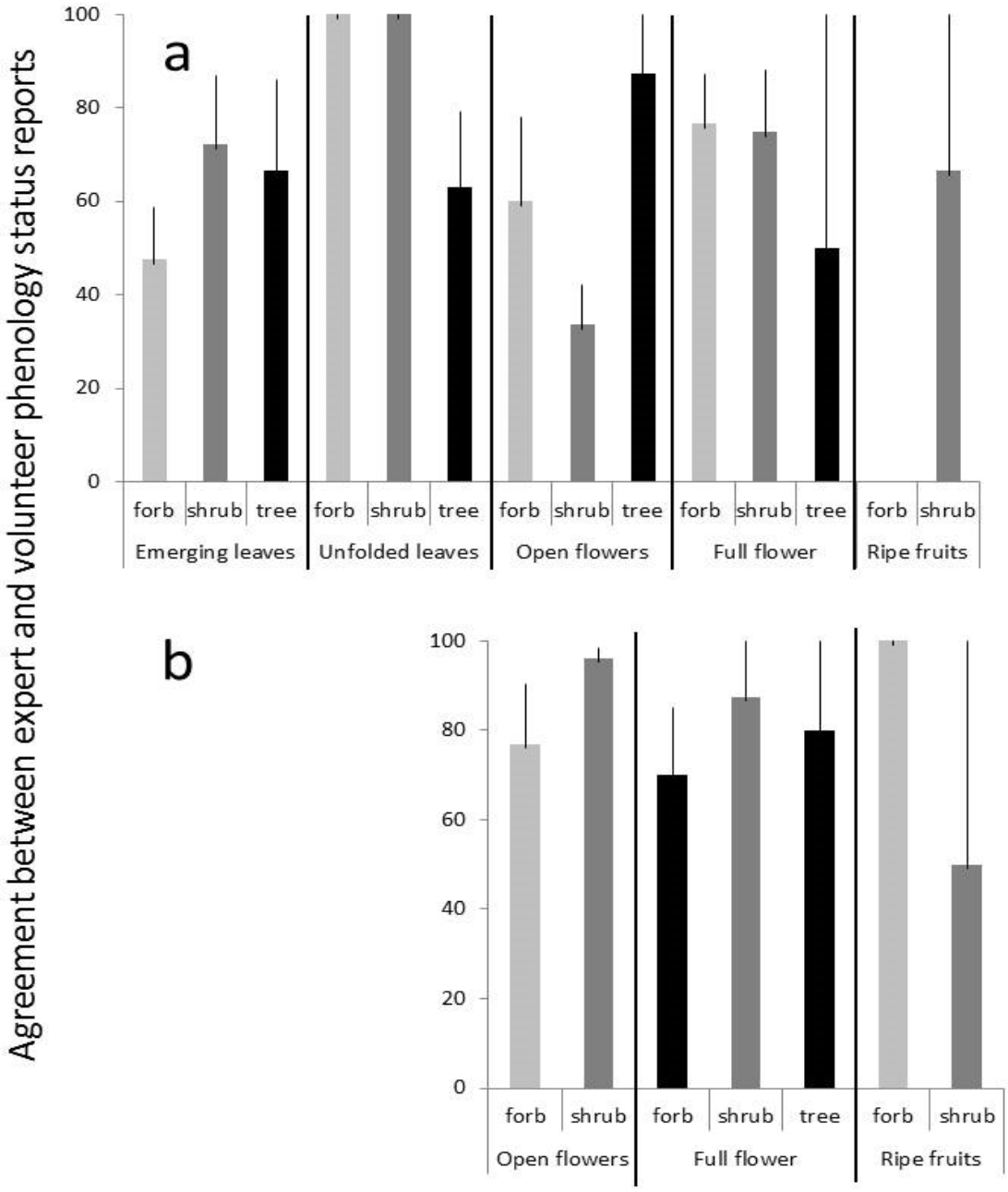


Figure 2.3. Agreement between project leader and volunteer participants' reports of plant phenology status during phenophase transitions from a) not occurring ("no") to occurring ("yes") and b) from occurring ("yes") to not occurring ("no"). The number of observations is depicted in parentheses under each functional group on the x-axis.

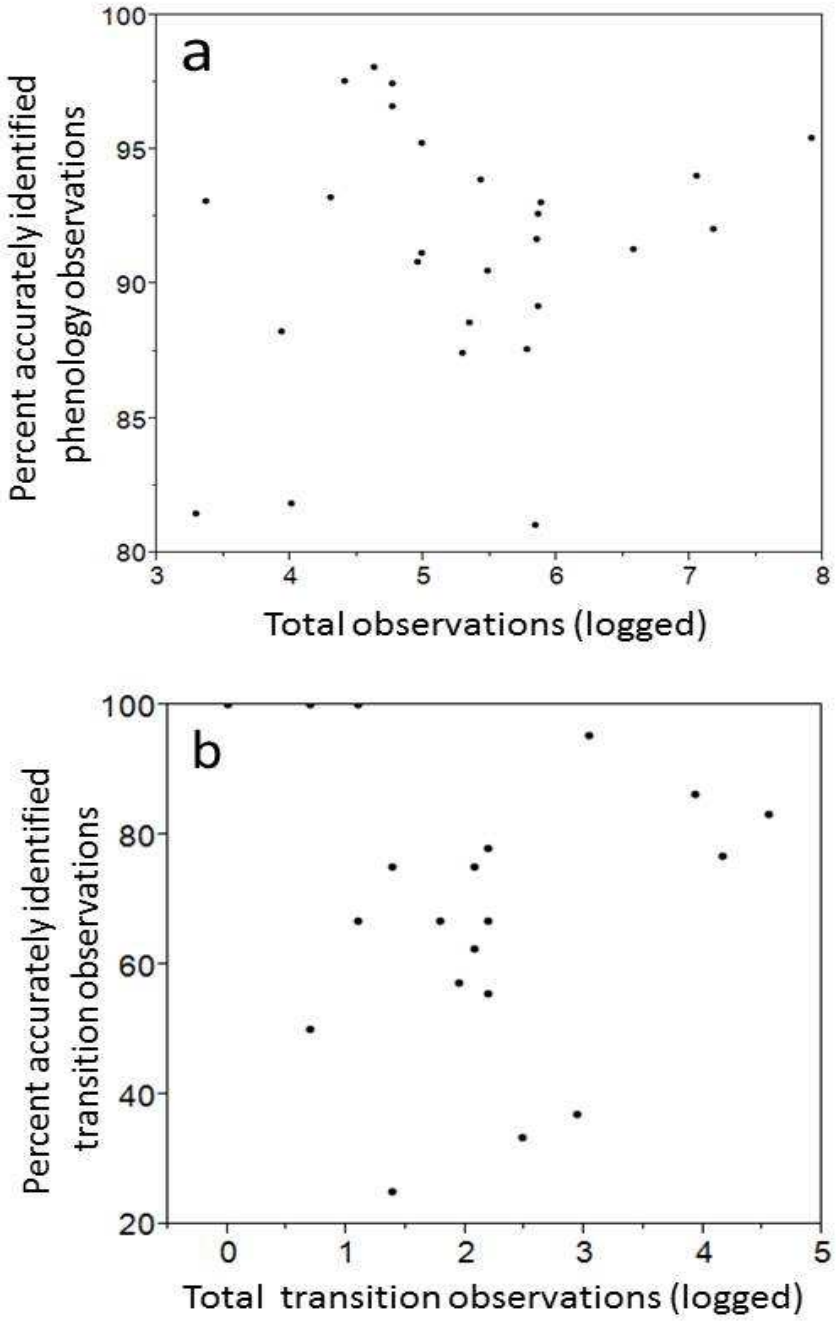


Figure 2.4. Linear fit between a) the observer's overall accuracy and the number of observations reported by an observer over the course of the season, and b) the observer's accuracy at correctly identifying transitions and the number of phenophase transition observations reported by an observer over the course of the season (R^2=0.06; p=0.19).

Chapter 3.

The role of functional diversity in restoring patches of pollinator habitat: how plant diversity and nectar availability affect pollinator visitation and seed set

Introduction

Habitat loss, fragmentation, altered land use, introduction of invasive species and climate change threaten some plant and pollinator species and the interactions between them (Aguilar et al. 2006, Goverde et al. 2002, Kearns et al. 1998, Miller-Rushing & Inouye 2009, Nattero et al. 2010). Disruptions in plant-pollinator mutualisms could have dire consequences for natural and managed ecosystems, as well as impair the ecosystem service that humans rely on for adequate food supply (Bronstein et al. 2004, Memmot 2007, Mitchell et al. 2009, Nabhan & Buchmann 1996). Maintaining and restoring pollinator habitat connectivity across landscapes—through stepping stones (patches of pollinator habitat), corridors, or buffers—could mitigate some of the decline caused by fragmentation and habitat loss (Menz et al. 2011). More theoretical and empirical research is needed to adequately inform the design of measures intended to improve habitat quality and connectivity (Burgess 2013, Tuell et al. 2008).

Studies have shown that hedgerows, corridors and cover crops, especially those that contain diverse plant species and abundant floral resources, can provide improved forage opportunities and enhanced pollinator migration, colonization, and persistence in agricultural environments (Kremen et al. 2007, Tuell et al. 2008). This finding extends to other managed and urbanized areas: increasing the availability and diversity of floral resources can augment pollinator abundance and diversity (Ahrné et al. 2009,

Blackmore & Goulson 2014, Lowenstein et al 2014, Matteson et al. 2008, Matteson & Langellotto 2010, Pardee & Philpott 2014, Hicks et al. 2016).

These results lead to the question, which ecological variables should managers prioritize when planting pollinator habitats, particularly patches in fragmented landscapes? Is it more effective to prioritize diversity alone, or to prioritize the inclusion of species with key traits, such as 'high-resource' (i.e., high nectar or pollen-producing) 'magnet species' (species particularly attractive to pollinators, whether through nectar, visual display, or odor)? These questions are difficult to answer because most studies do not isolate the effects of plant diversity alone from functional diversity, patch size, or surrounding landscape factors. Although biodiversity is associated with ecosystem services and productivity (Cardinale et al. 2012, Duffy et al. 2017), diversity alone does not necessarily translate to ecosystem function, including the provision of pollinator habitat—rather functional and phylogenetic diversity are often more important that just species richness alone (Kremen et al. 2007, Neame et al. 2012, Thompson et al. 2015). In some cases, high plant diversity can actually be counterproductive for pollination—it can contribute to competition and stigma clogging, as some pollinators do not visit the same species of flowers successively on individual foraging trips (floral constancy) (Rathcke 1998, Waser 1978).

The questions of which plant traits to prioritize are particularly important when restoring small patches of pollinator habitats, which is common in rural, suburban, and urban areas. Large patches of habitat and patches surrounded by relatively intact natural landscapes generally contain more diverse floral resources and greater habitat connectivity and hence support more diverse pollinator assemblages (Blaauw & Isaacs,

2014, Sabatino et al 2010, Sih & Baltus 1987). Because it is not always feasible to restore large areas, farmers, resource managers, and other conservation-minded organizations and individuals frequently establish small patches that can function as stepping stones in connecting larger habitat patches across the landscape.

In restoring small patches of pollinator habitat, high-quantity and quality nectar or pollen (high-resource magnet species) and long-duration flower displays are key functional traits (Baude et al. 2016, Comba et al. 1999, Willmer 2008). These traits can influence pollinator foraging behavior, which in turn can affect pollen dispersal patterns and plant reproductive success (Campbell & Dooley 1992). For example, the floral display or high nectar concentration of one species can draw pollinators to a patch of plants. Those pollinators might visit neighboring species within the patch—pollinators very typically move short distances between flowers, even of different species—increasing pollination for all of the species, even ones less attractive to pollinators (e.g., those with lower nectar concentrations). This process is called 'pollination facilitation' or the 'magnet effect,' and has been shown in multiple systems to varying degrees (Laverty 1992, Molina-Montenegro et al. 2008, Peter & Johnson 2008). Some studies show that multispecies floral displays can enhance pollination facilitation, leading to increased fitness of co-flowering species (Rathcke 1988, Schmeske 1981). For example, Ghazoul (2006) found an increased number of insects visiting *Raphanous raphanistrum* flowers in mixed-species over single-species plots, demonstrating heterospecific facilitation of pollination. However, in some cases, species compete for pollinators, rather than facilitate the pollination, limiting reproductive success of less attractive plants (Ashman et al. 2004, Menz et al. 2011, Moragues & Travaset 2005, Waser 1978).

Interspecific pollen transfer can also lead to a loss of pollen for individuals of both species when the pollen is deposited on unviable stigmas (Aizen & Ashworth 2002, Luijten et al. 2000, Waser 1978). Without empirical testing, it is difficult to predict if plant species that share pollinators will interact competitively or facilitatively.

We examined how these theories about diversity and biotic interactions apply to pollination in restored patches of native plant communities through three lines of inquiry: (1) How do plant diversity and the presence of high-resource (nectar-rich) species affect pollinator diversity and abundance in multi-floral species patches with identical size and floral abundance? And which factor, plant diversity or the presence of high-resource plants, has a larger effect? (2) Does the presence of high-resource plant species influence visitation rate and seed set of low- or intermediate-resource species (i.e., facilitation via common pollinators or the magnet effect)? (3) Does plant diversity influence pollinator visitation and seed set of high-resource plant species?

We hypothesized that patches with high plant diversity would attract higher diversity of pollinators, but that patches with high concentrations of high-resource (nectar-rich) plants would support the highest abundance of pollinators. We also hypothesized that low- and intermediate-resource species would experience more visitation from pollinators and higher seed set when they co-occur with high-resource species (because of the magnet effect), and that high-resource species would experience less visitation and lower seed sets in high-diversity patches due to competition or stigma clogging. The results are intended to inform ecological theory related to the influence of ecological traits on pollination, and to inform the design of projects to restore pollinator and native plant habitats.

Materials and Methods

Species selection

Species were selected through a multistep process. High and intermediate-resource species were chosen by compiling lists of "pollinator plants" and marking whether they were considered "high" or "medium" value by at least 3 reputable sources (e.g., Xerces Society, Pollinator Partnership, Lady Bird Johnson Wildflower Center, US Department of Agriculture Natural Resource Conservation Service). Pollinator plant lists are usually generated with support from empirical research on nectar (and sometimes pollen) value per species. While both nectar and pollen are important floral resources, nectar volume is most commonly evaluated in pollinator plant resource levels because of its importance as an energy source in the diets of most adult insect pollinators, and because it provides a common currency (total sugars) by which researchers can express the nutritional contribution of all plant species (Willmer 2008). Thus, species we identify here as high-resource species are nectar-rich species (but may also be high-value pollen species as well). Low-resource species were chosen if they were not found on any pollinator plant lists and had cited literature discussing lack of nectar or low-value pollen. The list of potential species was refined by timing of flowering. All species had to co-flower during the same three-week span (from July 23th –August 16th).

All selected plant species were generalists with respect to their pollinators and experienced a range in pollinator group-level visitation (bees, butterflies, wasps, and flies). Some species had more specialized attributes than others (e.g., *Phlox maculata* is generally more attractive to butterflies than bees), but no plant species had an obligate

pollinator relationship as determined by literature and field observations. Species included self-compatible and self-incompatible species, in terms of pollination, and included species that are common and those that are rare on the landscape surrounding the study site. All species flower abundantly, are commonly found in native plant gardens, and are readily available at native plant nurseries. The list was further refined by visits to plant nurseries to corroborate literature on pollinator resource value. Ten-minute observation periods per plant species helped us assess and confirm frequency of floral visitation by a range of pollinators. The list was finalized by quantity and availability of desired species meeting the above listed requirements at native plant nurseries within a range of 100 miles of the experimental site (Table 3.1).

Patch treatments

Following a fully crossed two-factor experimental design, we established four patch treatments. High-diversity, high-resource (**HD-HR**) patch: 7 different plant species, including 3 of which are considered high-resource (nectar-rich) species, 2 showy, intermediate-resource species, and 2 low-resource species that are rare on the landscape. Low-diversity, high-resource (**LD-HR**) patch: 3 high-resource species. High-diversity, low-resource (**HD-LR**) patch: 6 different species, including 3 showy, intermediate-resource species, and 3 low-resource species, 2 of which are rare on the landscape. Low-diversity, low-resource (**LD-LR**) patch: 3 low-resource species, 2 of which are rare on the landscape. (Table 3.1, Appendix A.1).

Experimental design

In July of 2014, on a large 2.5-hectare field in the Catskill Mountain region of New York, USA, four treatments were established in each of 4 different quadrants on a regularly mowed field (to limit effects of other floral resources), yielding 4 replicates per treatment across a total of 16 patches. Patches were distributed within each replicate and across the 4 replicates in a Latin Square design so that they would not have repeat positions in relationship to the woodland edges. The 4 treatment patches were laid out 20 meters from each other patch within the replicate and 40 meters from neighboring replicates (4 replicates total). Each circular patch had a diameter of 2.5 meters (to represent a common size for urban/residential pollinator gardens). Environmental influences such as distance to edge, duration of direct sun exposure (aspect) and within-patch floral density were kept relatively constant between patches. Distance to the edge was 10 m for the outer patches and 30 m from the nearest edge for the inner patches. Patches were placed so that each treatment replicate had a position on an outer and inner corner as well as all directional edges. (Figure 3.1).

Replicate individuals of each species were bought from 5 different native plant nurseries and were marked with identifiers and randomized throughout patches so that self-incompatible species always had genetically different individuals that they could readily cross-pollinate with. Within patches, individual pots were sorted by abundance of flowering stems to ensure that patches maintained a relatively constant total floral density throughout the experiment (range was between 50-80% floral density across patches at all times, but most consistently between 65%-75%). Not-yet-blooming stems of focal species in each category were randomly tagged with identifiers (for measuring

open pollinated and hand-pollinated seed set) and a proportion of not-yet-blooming stems were randomly tagged and bagged with transparent mesh bags (for hand-pollination). Patches were all watered every day at 6:30 pm.

Observation of pollinator visitation

All observations were conducted 25 July through 14 August 2014 during optimal pollinator foraging conditions (weather: partly to fully sunny, temperatures between: 21-32 degrees Celsius). All observations were taken between 10:00 and 18:00 for optimal pollinator activity and consistency in sun exposure across all 16 patches. Observations were randomized so that treatment patches would be observed at various times throughout the day to minimize bias introduced by differential activity relating to time of day. Fourteen observation days were logged yielding 56 observation units per treatment (224 observation units across all patches). Each patch was observed for 25 minutes each day, for a total of 93.3 hours of observation time over the field season for all 16 patches. Preliminary field identification of floral visitors was done using mostly live capture and photography. Field identification conducted during experiment was done "on the wing" and with macro photography; photographed specimens were later identified using a combination of field guides, experts and online resource (bugID.net).

Total observation period per treatment patch spanned 25 minutes, 19 of which were used for analyses reported in this chapter. The observation period consisted of four parts: 1 minute scan for initial overall number of pollinator individuals (not used here); 4 minutes to assess total patch floral density (with a grid – stand on 4 sides of patch) and inflorescence count per plant species; 15 minutes to tally visitor abundance and diversity

per plant species; 5 minutes observing visitor foraging behavior (not used in this analysis).

Seed set measurement

Three species (representing each resource level), were chosen to measure seed set due to perceived ease of ability to measure viable seed and number of individuals available to place evenly within treatment patches. *Liatris spicata,* the high-resource species chosen to determine effects of competition was placed in HD-HR and LD-HR treatment patches and *Phlox maculata*, the intermediate resource species chosen to evaluate facilitation was placed in HD-HR and HD-LR patches. The low-resource species *Filipendula rubra*, was chosen as the low resource test species for facilitation and was placed in HD-HR, HD-LR, and LD-LR patches; however, its seed set was not viable in any of the treatments, very likely due to minimal genetic diversity across nurseries (which we were not aware of at the start of the experiment), so did not produce viable results and were not analyzed. Stems of each of these three focal test species were bagged in random patches within each treatment that housed them for hand-pollination to serve as a control. During the experiment bagged flowers for hand pollination were assessed daily; when in bloom they were outcrossed and re-bagged. Other pre-tagged stems were allowed open-pollination. When open-pollinated stems dehisced, they were bagged and left to ripen. All bags were taken down after experiment and each inflorescence of each pre-tagged stem was evaluated for seed set.

Statistical analyses

All statistical analyses were carried out in SAS software program JMP version 13. All variables were visually checked to determine if they met assumptions of normality and homoscedasticity then transformed, if needed. To evaluate whether pollinator abundance and pollinator diversity varied significantly across patch treatments with varied plant species composition and level of diversity, we performed a Mixed-Model ANCOVA with date as a nested random effect in the model. Pollinator abundance had an approximately normal distribution and normality for pollinator diversity was achieved by squaring the data values. Plant diversity (fixed: high or low), plant resource level (fixed: high or low), floral display percentage (continuous), wind (fixed: medium, low or none), weather (fixed: partly sunny, mostly sunny or sunny) and temperature (continuous) were included as explanatory variables in the model. Planned pairwise comparisons between all treatment means were tested using Tukey-Kramer-HSD to evaluate whether plant diversity level or plant resource level had a stronger effect on pollinator abundance and pollinator diversity.

To assess facilitation/magnet effect and competition, we evaluated the pollinator visitation rate per focal plant species in high versus low diversity and high versus low resource treatment patches. To do this, we performed a Mixed-Model ANCOVA with date as a nested random factor for each focal species (2 different species per resource category) and number of flowers (total open inflorescences per species) wind, weather, temperature, and patch treatment as covariates in the model. Post-hoc analyses compared pairwise means among treatments per focal species (Tukey-Kramer-HSD). To evaluate seed set for focal high resource and intermediate resource species, we ran a t-

test between treatment patches and verified differences between treatment patches and hand-pollinated controls using the post-hoc Tukey-Kramer HSD.

Results

Key: High Diversity-High Resource (HD-HR), Low Diversity-High Resource (LD-HR), High Diversity-Low Resource (HD-LR), Low Diversity-Low Resource (LD-LR).

Effects of plant resource level and diversity on pollinator diversity and abundance

The ANCOVA results indicated that pollinator diversity and abundance (visitation rate) varied significantly across treatment patches. Both treatment variables (resource level and diversity) and their interaction explained significant amounts of variation in pollinator diversity and abundance (Table 3.2, Table 3.3). Environmental variables (wind, weather, temperature), were not significant, with the exception of wind (medium category) for pollinator abundance only ($p < 0.047$). Pollinator visitation was affected by sampling date at both the patch level (variance Estimate 22.6% for pollinator abundance and 15.5% for diversity) and species level (variance estimate range for the 6 focal plant species was 12-35%) (Tables 3.2 and 3.3). The effect of sampling date on pollinator visitation was similar across treatments (Figure 3.2).

Both high-resource treatments (HD-HR, LD-HR) had the highest abundance and diversity of insect pollinator visitors and the high-diversity treatment in the low-resource category had higher pollinator abundance and pollinator diversity than did the low-diversity treatment (Figure 3.3, Figure 3.4). Post-hoc analyses revealed that all patch treatments for both pollinator abundance and pollinator diversity were significantly different from each other ($p < 0.001$) with the exception of the two high resource

treatments (HD-HR and LD-HR) ($p = 0.17$, $p = 0.97$ respectively, Tukey-Kramer HSD), suggesting that for high resource treatments a higher level of plant diversity did not have a strong effect on the abundance or diversity of insect visitors (Table 3.4).

Pollinator abundance and diversity between LD-LR and HD-LR treatments were significantly different from each other (Tukey HSD; $p < 0.001$ for each), indicating that at lower resource levels, increased plant diversity may increase pollinator abundance and diversity (Table 3.4). Differences in pollinator abundance and pollinator diversity were significantly different between HD-HR and HD-LR treatments (Tukey HSD; $p < 0.001$ for both), indicating that high resource species may significantly increase pollinator abundance and pollinator diversity in patches with similarly high diversity levels. Pollinator abundance and diversity between LD-LR and LD-HR treatments were significantly different from each other (Tukey HSD; $p < 0.001$, $p < 0.001$), indicating that the presence of high resource species can significantly increase pollinator abundance and pollinator diversity even at low plant diversity levels (Table 3.4).

Pollination facilitation

Comparisons of individual species within pairs of the patch treatments revealed the extent to which different plants experienced facilitation or competition with each other. Differences across patch treatments were significant for both low-resource species, *Coreopsis rosea* ($F_2 = 7.30$, $p < 0.01$) and *Filipendula rubra* ($F_2 = 16.13$, $p < 0.01$). *Coreopsis rosea* showed no significant difference in pollinator visitation between HD-HR and either the LD-LR or the HD-LR treatments; however, *C. rosea* had significantly higher pollinator visitation in the HD-LR treatment than the LD-LR treatment (Tukey

HSD; $p = 0.01$), indicating that a high-diversity patch with intermediate-resource species present facilitated pollinator visitation the most to the low-resource *C. rosea* (Table 3.5). For *C. rosea*, it appears that the presence of intermediate-resource species may have had a more facilitative effect than the presence of high-resource species. There was no significant difference in pollinator visitation to *F. rubra* between LD-LR and HD-LR treatments; however, the HD-HR treatment had higher pollinator visitation than both the LD-LR treatment (Tukey HSD; $p < 0.01$) and the HD-LR treatment (Tukey HSD; $p < 0.01$), indicating that the presence of high-resource species likely facilitated pollinator visitation to *F. rubra*, as opposed to diversity or presence of intermediate-resource species (Figure 3.5). Seed set data for *F. rubra* was zero, including for hand-pollinated control.

Differences across resource treatments were not significant for intermediate-resource species *Veronicastrum virginicum* ($F_1 = 0.87$, $p = 0.35$) and *Phlox maculata* ($F_1 = 1.82$, $p = 0.18$). Pollinators did not visit *V. virginicum* or *P. maculata* at different rates when resource level varied but diversity was high (Tukey HSD, HD-HR versus HD-LR; $p = 0.16$, $p = 0.41$, respectively), indicating that intermediate-resource species did not experience facilitative effects by being in treatment patches with high-resource species (Table 3.5, Figure 3.6). The seed set experiment, however, showed that the HD-LR treatment containing intermediate- and low-resource species had the highest seed set for *P. maculata*. Seed set for focal intermediate-resource species *P. maculata* was significantly different between high-resource and low-resource patches with the same level of plant diversity ($t=2.12$, $n=68$, $p < 0.0001$). Post hoc Tukey-Kramer HSD analysis confirmed that seed set for *P. maculata* was significantly different between

patches and hand-pollinated control ($p < 0.001$), indicating that *P. maculata*, a self-incompatible intermediate-resource species, does not appear to have experienced facilitation and subsequent increased seed set while in patches with high-resource species as hypothesized, and that high-resource species may have increased competition for visitation to *P. maculata* (and reduced seed set) (Figure 3.7).

Competition for pollinators

The two high-resource species we monitored to evaluate competition, *Liatris spicata* and *Monarda fistulosa*, experienced significantly more pollinator visits in some treatments than others ($F_1 = 18.92$, $p < 0.01$ and $F_1 = 16.97$, $p < 0.01$, respectively). Both species had significantly lower visitation in the HD-HR treatment than in the LD-HR treatment—*L. spicata* (Tukey HSD; $p < 0.01$) and *M. fistulosa* (Tukey HSD; $p < 0.01$)—indicating that both high-resource species likely experienced increased competition for pollinators in high-diversity patches (Table 3.5, Figure 3.8). However, the seed set for focal high-resource species *L. spicata* was not significantly different between high-diversity and low-diversity patches with the same resource level ($t = 0.733$, $n=240$, $p = 0.46$) (Figure 3.9). Post hoc Tukey-Kramer HSD analysis confirmed that seed set for *L. spicata*, a self-incompatible species, was not significantly different between treatment patches ($p=.4642$), but was significantly different between each treatment patch and the hand-pollinated control ($p < 0.0001$). Though visitation data indicated that *L. spicata* received less overall pollinator visitors while in high-diversity patches, this possible increase in competition for pollination services did not seem to affect seed set for *L. spicata.*

Pollinator diversity

A calculation of the percentages for the top five most abundant pollinator species visiting each treatment revealed that the dominant pollinator community was similar across all treatments, indicating that there were no specific species driving differences in pollinator diversity among treatment patches. The treatment that attracted the most different pollinator assemblage was the HD-LR treatment, which contained one plant species that was different from the other treatments. This plant species, *Rudbeckia hirta*, was mainly responsible for the difference in pollinator assemblage as it appeared to be favored by two specific pollinator species (Table 3.6). Honeybees, syrphid flies and bumblebees were the most common visitors to all patches; as a group, bees (honeybees and native bees) were more prevalent across patches than butterflies/skippers, and flies, though flies (Syrphidae as a whole) accounted for the highest visitation to the LD-LR treatments, indicating that perhaps this pollinator group prefers to forage in less competitive environments, even when resource level is sub-optimal.

Discussion

This study demonstrated that in small-scale plant restoration sites, plant diversity and resource (nectar) availability can significantly affect the abundance and diversity of pollinating insects. Specifically, the presence of high-resource (nectar-rich) plant species increased pollinator abundance and diversity. Plant diversity increased pollinator diversity and abundance only in the absence of high-resource plants. Pollination facilitation varied among species: one low-resource plant species benefited from high

diversity without high-resource plants; another benefited from high diversity with high-resource plants; and the intermediate-resource plant species performed similarly in terms of pollinator visitation and seed set in all treatments. Competition for pollinators did not affect seed set for high-resource plants in any of the treatments. The community of most common pollinators was fairly consistent across all of the treatments, indicating that select species were not driving differences across patches. The environmental variables we tested (temperature, weather, wind) were not significant because observations were only taken on optimal pollinator foraging days and affected each of the treatments in the same way (e.g. windier days had less pollinator visitation across all treatments).

Together, these results suggest that managers or landowners who are restoring patches of native plants as habitat for pollinators should prioritize including high-resource species (species with high nectar/pollen production), and secondarily, a diverse mix of species, if space and resources allow. Many pollinator planting operations currently use diverse seed mixes (Hicks et al. 2016); our study suggests it is important that they prioritize including high-nectar-producing species in the mixes, and/or consider focusing efforts on obtaining plugs of high resource species to maximize this key functional trait when space is limited.

Examining facilitation and competition

Overall, pollinator visitation to low-resource species was higher in patches with high- or intermediate-resource species, suggesting that facilitative effects (or the magnet species effect) did occur for different resource levels. However, the circumstances that facilitated pollination of low-resource species varied among species. *Filipendula rubra* (queen of the prairie) had more visits and higher seed set in high-diversity patches with

high-resource species. *Coreopsis rosea* (pink tickseed) received more visits and higher seed set in patches with intermediate-resource species, but not high-resource species. Thus, in cases where managers or landowners are attempting to maximize pollination of low-nectar producing plants (e.g., if these species are of conservation concern), it appears that each species should be evaluated individually.

Pollinator visitation rate to high-resource species was lower in high-diversity patches—a sign of competition for pollinators—but this lower visitation had no effect on seed set. This suggests that these high-resource species can persist or be planted in high-diversity patches, providing benefits for some low-resource plant species (such as *Filipendula rubra*) and supporting a high diversity of pollinators with no evident negative effects on the seed set of high-resource species.

For species of conservation concern that do not produce much or any nectar and may not be attractive to pollinators, facilitating pollination by co-planting with nectar-rich species with similar flowering phenology could serve as a valuable conservation technique (Bertness & Callaway 1994, Lever 2014 et al.). Increased pollinator visitation could enhance cross-pollination, genetic health, population growth, and regeneration by seed, and could also mitigate Allee effects (in this case, reduced reproductive rates due to small population size) (Ghazoul 2006). Though some native plants may not be high resource plants for pollinators, they can have high value to other wildlife (e.g., seeds may be important food for birds in winter). By intentionally increasing seed set through facilitation in targeted pollinator patches, overall ecosystem value of certain plant species could increase on a landscape-scale.

Study limitations and other considerations

The narrow questions of this study limited our selection of plant species—we had to select plant species that flowered at the same time (over the same few weeks in the summer) and kept the floral display relatively consistent from patch to patch. Thus, we sampled only pollinators that were active at that time. It is possible that the results (particularly pollinator diversity and behavior) could differ for restoration patches with assortments of plant species that flower during different seasons (e.g., early spring vs. mid-summer). We recommend that future studies repeat these tests with different mixes of species in different parts of the growing season.

Because we identified pollinators primarily "on the wing" and through macrophotography, species-level identification was limited. We were able to fairly regularly identify some pollinator groups, such as butterflies and bumblebees, to species. However, some groups, such as syrphid flies and small native bees, we could often only identify to family or genus. This difference in taxonomic detail affects our calculations of diversity; however, because we were comparing relative diversity across treatments and there was only one field observer, we felt confident that species identification did not affect our conclusions substantially. Future studies could measure insect diversity more precisely, which would likely require destructive sampling of the insects.

In addition to diversity and nectar resources, several other patch characteristics influence pollinator activity in restoration patches and other habitat fragments. Patch size and shape, the presence of suitable nest sites, plant species composition, and surrounding landscape characteristics (including connectivity) can influence patch suitability for pollinators (Goddard et al. 2010, Menz et al. 2011, Pickett & Thompson

1978). The spatial layout of patches within landscapes, the interactions among them, and changes in the landscape also play key roles (Levin et al. 1993).

Conclusions and recommendations

Our investigation added to the rapidly moving study of how plant functional diversity can enhance the utility of restored patches of native plants to support pollinator and pollination services. In our case we found that nectar provision and plant diversity were key factors, and that effects of co-occurring with high-nectar plants and high diversity differed among plant species. These results can inform future plant and pollinator restoration efforts, helping managers identify appropriate characteristics for projects designed to mitigate fragmentation and habitat loss, and increase connectivity for plant and pollinator habitat landscape (Burgess 2013, Goddard et al. 2010, Vergnes et al. 2012). These strategies can be used in rural areas, where early successional habitat that is critical to many plants and pollinators is being lost; in urban landscapes, where most native habitats are lost, but many gardens, parks, and fragments of habitat are being restored; or along urban-rural gradients, including residential suburbs (Baldock et al. 2015, Blaauw & Isaacs 2014, Fontaine et al. 2005, Hennig & Ghazoul 2011, Kwak et al. 1998, Neame et al. 2012, Townsend & Levy 2005). Restored and enhanced pollinator habitats in these areas may act as important refuges and corridors for pollinators managed landscapes continue to expand (Baldock et al. 2015). Designing high-quality habitats at the local scale could potentially have profound effects on the diversity of pollination interactions at the landscape scale (Sabatino et al. 2010).

We believe that the approach used in our study can be replicated in future

restoration projects, including through citizen science. Replicating and expanding these types of studies can help evaluate the factors that influence the ecological function of habitat patches for plants and pollinators, how to optimize their design for restoration projects, and how best to scale restoration efforts. Pollinator gardens or patch plantings implemented by private residents or by schools, municipalities and conservation advocacy organizations (i.e. Xerces Society, National Wildlife Federation's Backyard Habitat Certification and the North American Butterfly Association's Certified Butterfly Garden program) are becoming increasingly common and could be opportunities for future study. Assessment of pollinator habitats using citizen-science friendly protocols (e.g. Xerces-Penn State 2008 Citizen Science Pollinator Monitoring Guide) could likely yield relevant information—the methods are not difficult, and there is great potential for education and stewardship. In our study, the patch assessment protocols we used to monitor pollinators were designed to be adoptable by observers with limited training (and have since been tested with citizen science observers).

Our study is an example of the kind of research at the patch level that can support and inform pollinator restoration efforts. Scaling-up from individual patches to increase connectivity across landscapes however, will require sustained, coordinated effort and more detailed analyses (Goddard et al. 2010). Research avenues that are amenable to collaboration and co-design between scientists and the dedicated stake-holders who champion these plant-pollinator restoration efforts will only serve to enhance coordinated and effective design needed to conserve plant-pollinator mutualisms across landscapes.

Chapter 3. Tables and Figures

Table 3.1. Species included in treatment plots, High-diversity, high-resource (**HD-HR**), Low-diversity, high-resource (**LD-HR**), High-diversity, low-resource (**HD-LR**), Low-diversity, low-resource (**LD-LR**). Status C (Common), R (Rare)

Species	Common name	Resource level	Status	HD-HR	LD-HR	HD-LR	LD-LR	Seed set
Liatris spicata	Dense blazing star	High	C	X	X			X
Monarda fistulosa	Wild bergamot	High	C	X	X			
Pycnanthemum muticum	Mountain mint	High	C	X	X			
Phlox maculata	Meadow phlox	Intermediate	C	X		X		X
Veronicastrum virginicum	Culvers root	Intermediate	C	X		X		
Rudbeckia hirta	Black-eyed Susan	Intermediate	C			X		
Filipendula rubra	Queen of the prairie	Low	R	X		X	X	X
Coreopsis rosea	Pink tickseed	Low	R	X		X	X	
Spirea tomentosa	Steeplebush	Low	C			X	X	

Table 3.2. Diversity (Shannon Index) of pollinators across all treatment plots (Mixed Model ANCOVA).

Variables	*df*	F	p-value
Resource Level (fixed)	1	516.11	***<.0001***
Diversity (fixed)	1	75.88	***<.0001***
Diversity x Resource	1	88.29	***<.0001***
Floral Display (%, continuous)	1	1.67	*0.1979*
Temperature (°C, continuous)	1	.232	*0.6312*
Weather (fixed)	2	.860	*0.4252*
Wind (fixed)	2	.055	*0.9468*
Random effect test	Variance/% Total	SE	Wald p-value
Date (nested random)	0.19/15.49%	0.11	0.080
Whole Model Effect:	RMSE	R^2	p-value
Pollinator Diversity	1.027	0.80	*<.0001*

Table 3.3. Pollinator abundance across all treatment plots (Mixed Model ANCOVA).

Variables	*df*	F	p-value
Resource Level (fixed)	1	522.14	***<.0001***
Diversity (fixed)	1	56.77	***<.0001***
Diversity x Resource	1	26.03	***<.0001***
Floral Display (%, continuous)	1	0.51	*0.4773*
Temperature (°C, continuous)	1	0.07	*0.7929*
Weather (fixed)	2	2.25	*0.1084*
Wind (fixed)	2	3.44	*0.0467*
Random effect test:	Variance/% Total	SE	Wald p-value
Date (nested random)	17.02/22.64%	8.91	0.056
Whole Model Effect:	RMSE	R^2	p-value
Pollinator Abundance	7.6266	0.79	*<.0001*

Table 3.4. Tukey-Kramer HSD ordered differences report for pollinator abundance (a) and diversity (b) (by treatment). Differences significant between all treatments except for the two high resource treatments

(a) Abundance

Treatment		Difference	p-value
HD/HR	**LD/LR**	**33.20**	***<.001***
LD/HR	**LD/LR**	**29.66**	***<.001***
HD/HR	**HD/LR**	**18.34**	***<.001***
HD/LR	**LD/LR**	**14.86**	***<.001***
LD/HR	**HD/LR**	**14.80**	***<.001***
HD/HR	LD/HR	3.54	0.168

(b) Diversity

Treatment		Difference	p-value
HD/HR	**LD/LR**	**4.68**	***<.001***
LD/HR	**LD/LR**	**4.59**	***<.001***
HD/HR	**HD/LR**	**2.85**	***<.001***
HD/LR	**LD/LR**	**1.83**	***<.001***
LD/HR	**HD/LR**	**1.74**	***<.001***
HD/HR	LD/HR	0.09	0.969

Table 3.5. Facilitation vs. competition output (ANCOVA) for 6 focal species.

Species	**Resource Level**	**R^2**	**Variables**	***df***	**F**	**p-value**
Coreopsis rosea	Low	0.25	Treatment	2	7.30	***<.01***
			Flower #	1	12.80	***<.01***
			Temperature	1	0.02	0.89
			Weather	2	0.79	0.46
			Wind	2	2.54	0.10
Random Effects	**Var Comp**	**%**	**SE**	Wald p-value		
Date	.29	8.1	.25	0.24		
Filipendula rubra	Low	0.37	Treatment	2	16.13	***<.01***
			Flower #	1	8.43	***<.01***
			Temperature	1	0.06	0.81
			Weather	2	0.08	0.93
			Wind	2	0.26	0.77
Random Effects	**Var Comp**	**%**	**SE**	Wald p-value		
Date	.37	16.2	.25	0.24		
Phlox maculata	Mid	0.38	Treatment	1	1.82	*0.18*
			Flower #	1	1.99	0.16
			Temperature	1	0.34	0.56
			Weather	2	0.18	0.83
			Wind	2	1.89	0.18
Random Effects	**Var Comp**	**%**	**SE**	Wald p-value		
Date	1.06	23.7	.71	.13		
Veronicastrum virginiana	Mid	0.54	Treatment	1	0.87	0.35
			Flower #	1	27.77	***<.01***
			Temperature	1	0.10	0.75
			Weather	2	0.72	0.49
			Wind	2	2.51	0.10
Random Effects	**Var Comp**	**%**	**SE**	Wald p-value		
Date	2.8	21.4	1.8	.13		

Liatris spicata	High	0.54	Treatment	1	18.92	***<.01***
			Flower #	1	17.17	***<.01***
			Temperature	1	2.26	0.14
			Weather	2	0.57	0.57
			Wind	2	2.85	0.08
Random Effects	**Var Comp**	**%**	**SE**	Wald p-value		
Date	3.93	18.1	2.7	0.14		
Monarda fistulosa	High	0.50	Treatment	1	16.97	***<.01***
			Flower #	1	3.39	0.07
			Temperature	1	0.16	0.69
			Weather	2	2.84	0.06
			Wind	2	1.51	0.24
Random Effects	**Var Comp**	**%**	**SE**	Wald p-value		
Date	4.7	29.7	2.6	0.7		

Table 3.6. Percentages of total pollinator visitation for top groups of pollinators per each patch treatment: High diversity-high resource (HD-HR), Low diversity-high resource (LD-HR), high diversity-low resource (HD-LR), and low-diversity, low-resource (LD/LR).

Pollinators	HD-HR	LD-HR	HD-LR	LD-LR
Apis mellifera	16.42	19.10	13.28	6.54
Syphrid flies (small)	14.35	5.10	23.63	58.08
Bombus impatiens	8.97	5.15	5.40	6.54
Bombus bimaculatus	9.49	9.11	1.92	3.07
Hesperiidae	9.34	18.22	2.93	5.77
Halictus	1.93	0.78	5.49	--
Phyciodes tharos	0.66	0.42	9.43	1.92

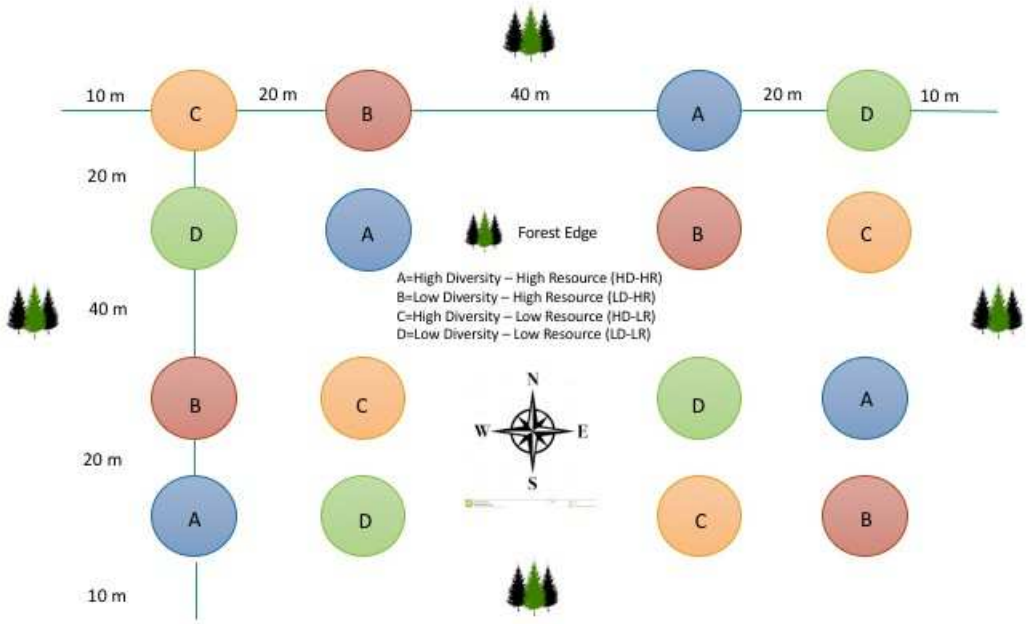


Figure 3.1. Replicate and patch design for treatments. Patches were placed so that each treatment had a position on outer and inner corners as well as all directional edges.

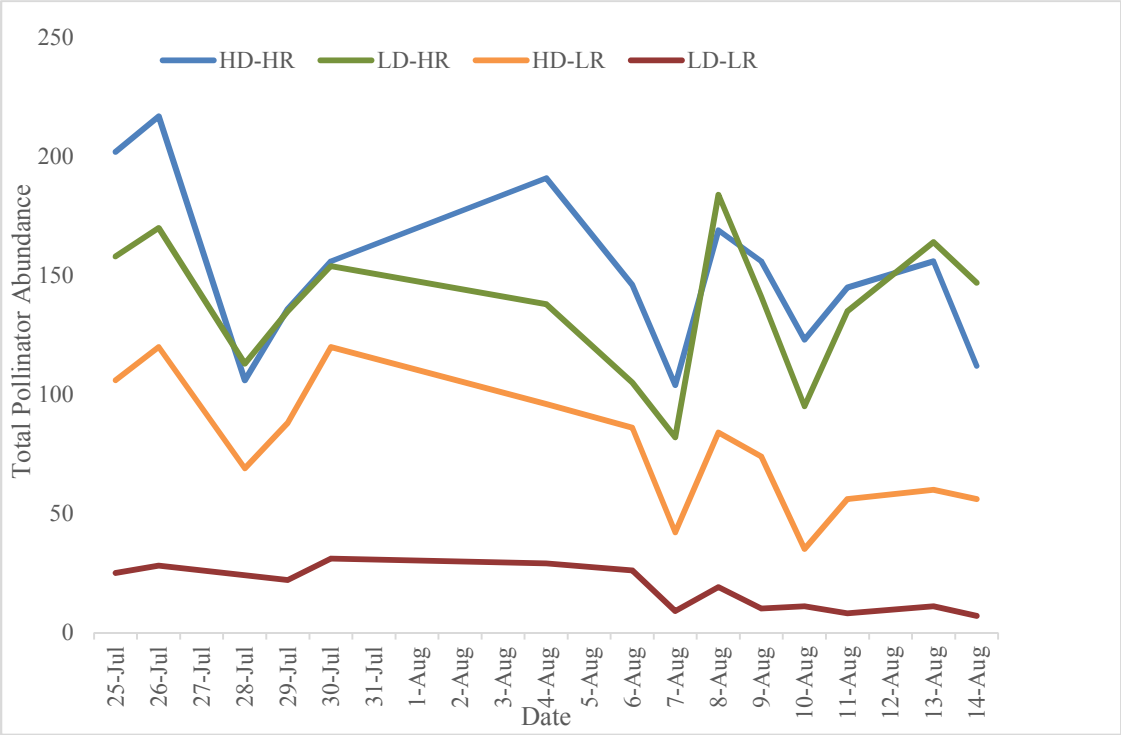


Figure 3.2. Total number of pollinator visitors for each treatment (High Diversity-High Resource (HD-HR), Low Diversity-High Resource (LD-HR), High Diversity-Low Resource (HD-LR), Low Diversity-Low Resource (LD-LR) per 76 min observations across four replicate patches per treatment per day (25 July -14 August, 2014).

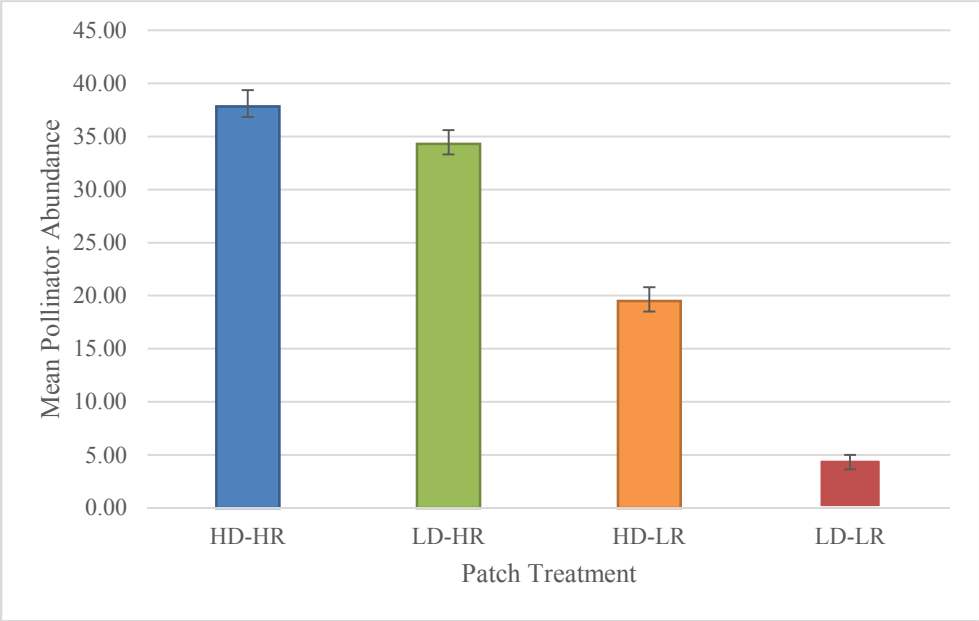


Figure 3.3. Abundance (mean ± SEM) of pollinator visitors for each patch treatment (High Diversity-High Resource (HD-HR), Low Diversity-High Resource (LD-HR), High Diversity-Low Resource (HD-LR), Low Diversity-Low Resource (LD-LR). All patch treatments for pollinator abundance are significantly different from each other ($p<0.001$) with the exception of the two high resource treatments ($p=0.1684$) Tukey-Kramer HSD, JMP13.

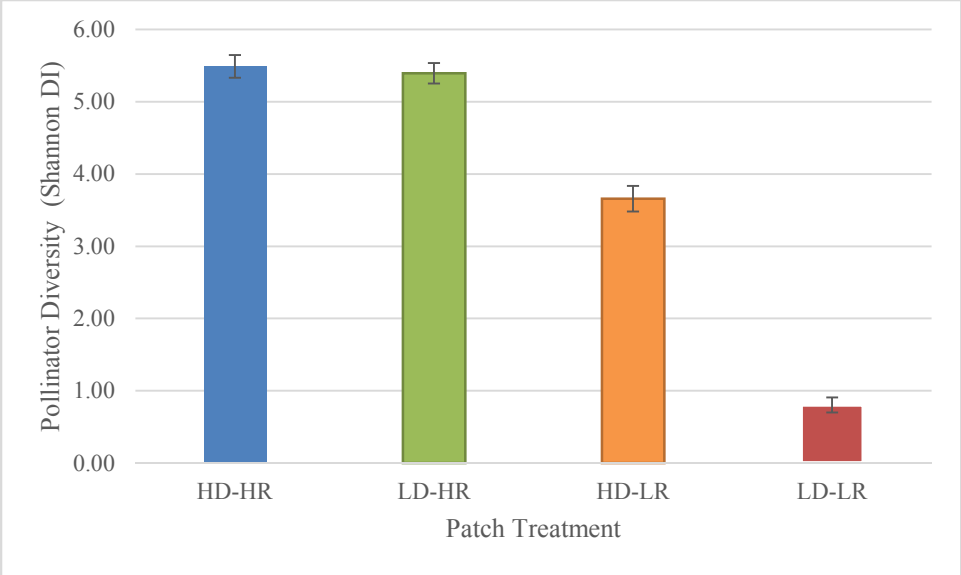


Figure 3.4. Shannon's diversity index values (mean ± SEM) of pollinator communities for each patch treatment (High Diversity-High Resource (HD-HR), Low Diversity-High Resource (LD-HR), High Diversity-Low Resource (HD-LR), Low Diversity-Low Resource (LD-LR). All patch treatments for pollinator diversity are significantly different from each other ($p<0.001$) with the exception of the two high resource treatments ($p= 0.969$) Tukey-Kramer HSD, JMP13.

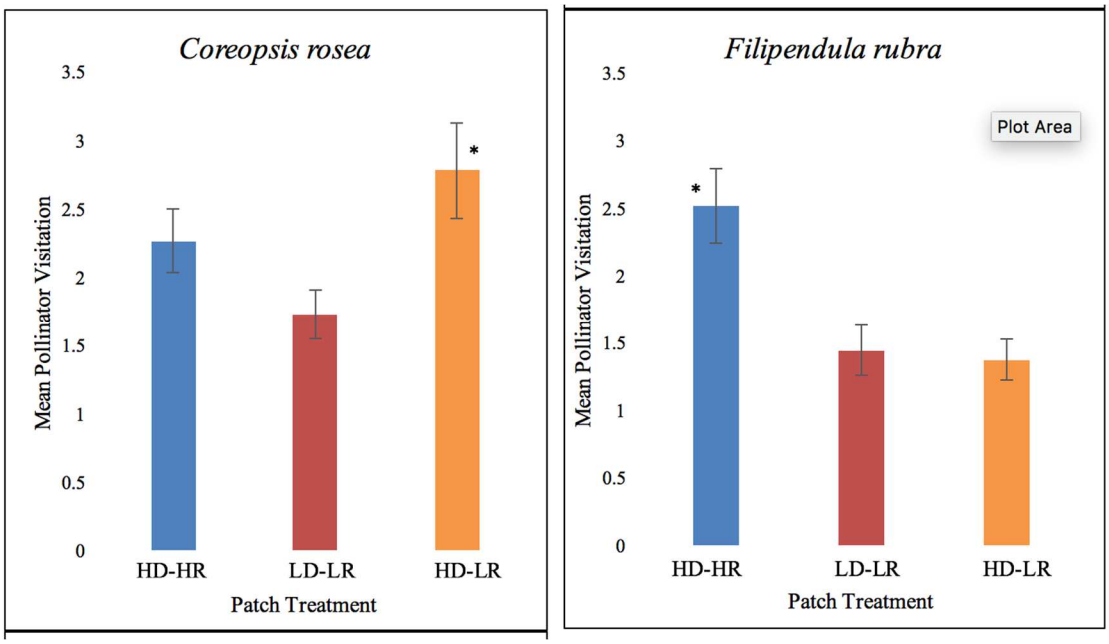


Figure 3.5. Facilitation to low-resource species *(mean ± SEM)*. Differences across patch treatments were significant for both *C. rosea* (F_2=7.30, p<.01) and *F. rubra* (F_2=16.13, p<.01). *C. rosea* showed no significant difference in pollinator visitation between high diversity-high resource (HD-HR) and low diversity-low resource (LD-LR), or high diversity-high resource (HD-HR) and high diversity, low resource (HD-LR); however, HD-LR treatment had significantly higher pollinator visitation than LD-LR (Tukey HSD; p=0.01), indicating that a high diversity patch with intermediate resource species present facilitated pollinator visitation the most to *C. rosea*. There was no significant difference in pollinator visitation to *F. rubra* between LD-LR and HD-LR; however, the HD-HR treatment had higher pollinator visitation than both LD-LR (Tukey HSD; p<0.01) and HD-LR (Tukey HSD; p<.01), indicating that high resource species may have facilitated pollinator visitation to *F. rubra*. The * indicates the treatment with significant differences.

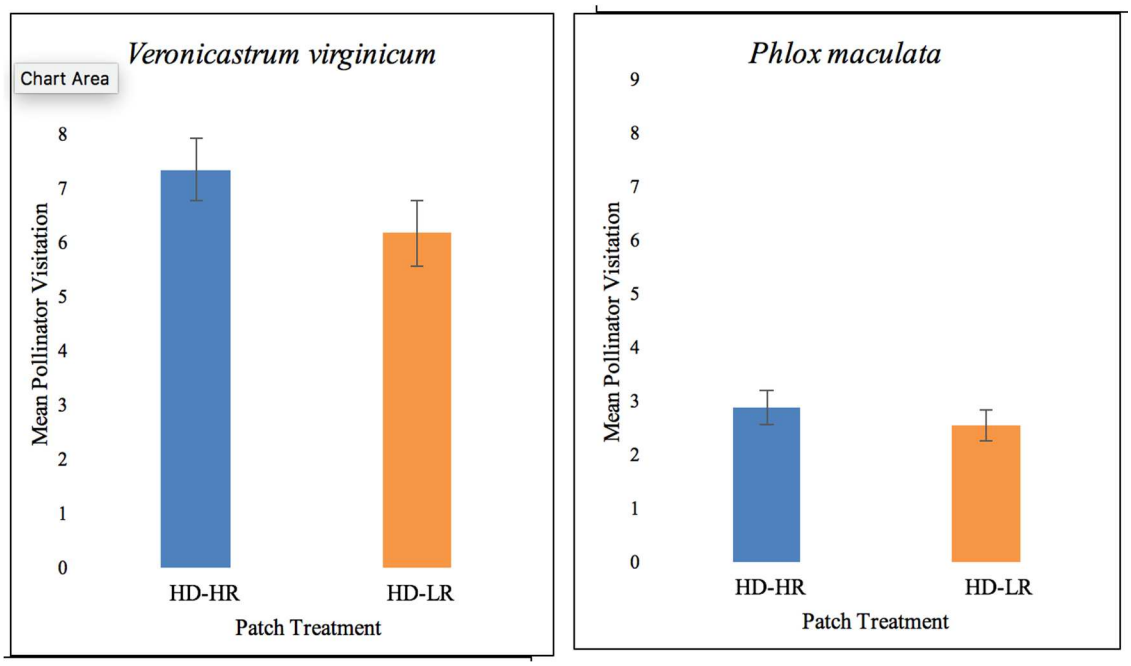


Figure 3.6. Facilitation to intermediate-resource species (mean ± SEM). Differences across resource treatments were not significant for intermediate resource species *V. virginiana* (F_1=0.87, p=0.35) and *P. maculata* (F_1=1.82, p=0.18). High diversity-high resource (HD-HR) and high diversity-low resource (HD-LR) treatments were not significantly different for *V. virginicum* (Tukey HSD; p=0.16) or *P. maculata* (Tukey HSD; p=0.41), indicating that intermediate resource species did not experience facilitative or competitive effects by being in treatment patch with high-resource species.

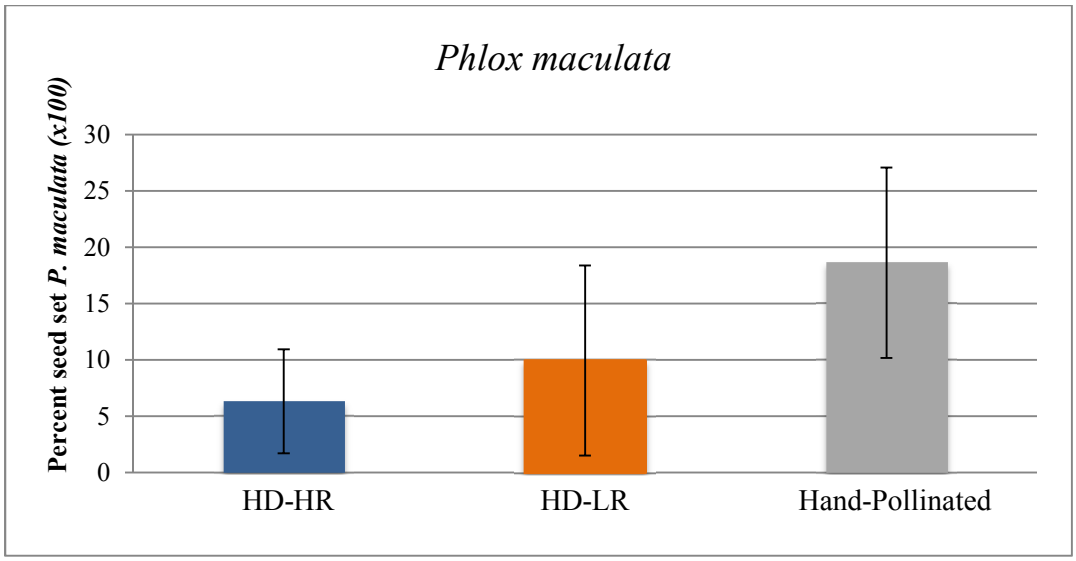


Figure 3.7. Seed set of the intermediate resource *P. maculata* (mean ± SEM) while in patch with high resource species (HD-HR) and without high resource species (HD-LR) ($t=2.12$, $n=68$, $p < 0.0001$), vs. Control (hand pollination) Tukey HSD $p<0.0001$). Seed set was higher in HD-LR than in the HD-HR treatment suggesting that high-resource species likely did not create facilitative effects for *P. maculata.*

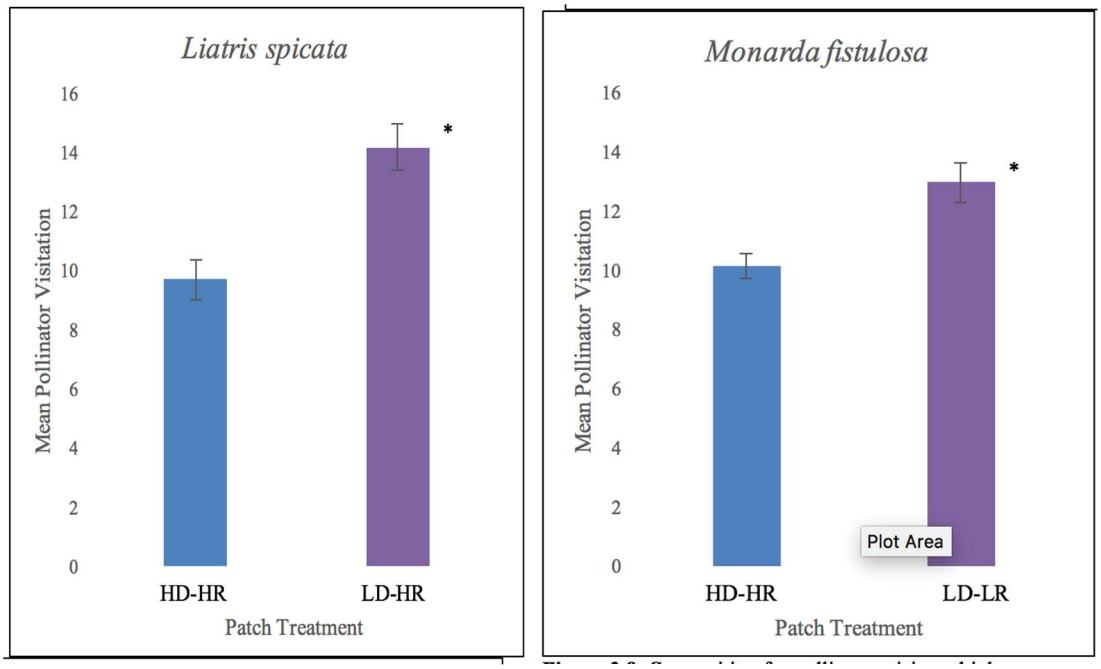


Figure 3.8. Competition for pollinator visits to high-resource species (mean ± SEM). Differences across patch treatments were significant for high resource species *L. spicata* (F_1=18.92, p<0.0001) and *M. fistulosa* (F_1=16.97, p<.01). High diversity-high resource (HD-HR) and low diversity-high resource (LD-HR) were significantly different for both *L. spicata* (Tukey HSD; p<.01) and *M. fistulosa* (Tukey HSD; p<.01), indicating that both high resource species experienced reduced visitation (and therefore pollen competition) while in a high-diversity patch. The * indicates the treatment with significant differences.

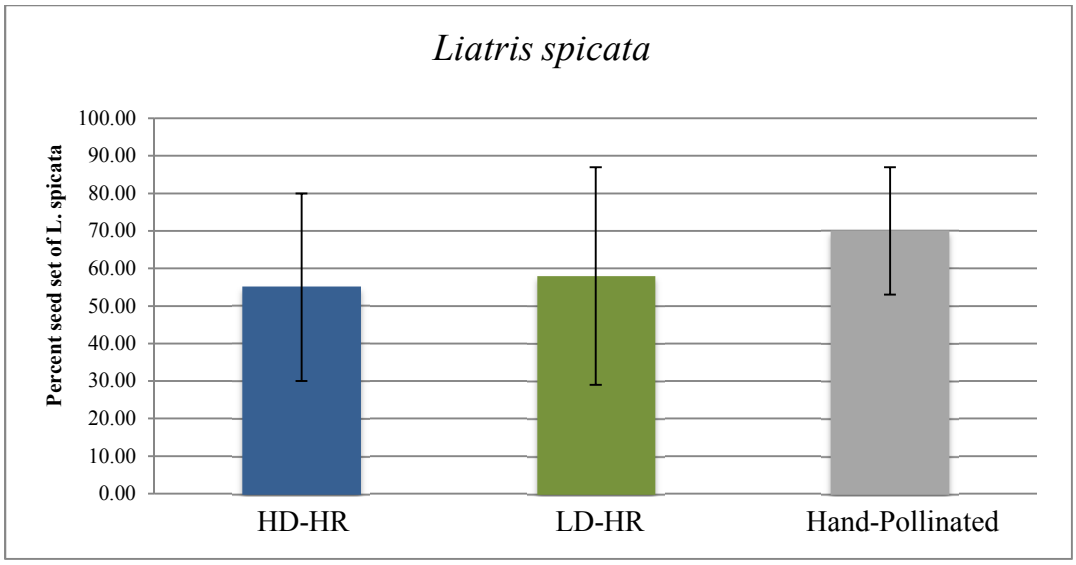


Figure 3.9. Seed set for the high resource species *L. spicata* (mean ± SEM) while in high-diversity and low-diversity treatment patches (t=.733 n=240, p<.4642) vs. hand pollinated control (Tukey HSD; $p < 0.0001$). Though visitation data indicated that *L. spicata* received fewer overall pollinator visitors while in high diversity patches, this possible increase in competition for pollination services did not seem to affect reproductive success for *L. spicata.*

Chapter 4.

Scaling citizen science: Utilizing large-scale data aggregation platforms to catalyze active regional networks

Introduction

Confirmation that citizen-scientists, with the right tools and clear instructions, can be deployed to collect reliable data for ecologically significant projects is an important finding for those seeking to scale big data sets (Bell 2007, Coster et al. 2015, Courter et al. 2012, Evans et al. 2005, Fuccillo et al. 2015, Galloway et al. 2006, Haklay 2010, Lovell et al. 2009, Sparks et al. 2008, Trumbull et al. 2000). We need to better understand, however, the specific ways to scale the work of these contributors and how to aggregate their efforts into efficient networks capable of sustaining disciplined data collection (Dickinson et al. 2012, Wiggins & Crowston 2011). Though appreciation for network theory in ecology is growing (Bascompte, 2007) and the field of citizen science is maturing rapidly (Bonney et al. 2009, Bonney et al. 2014, Dickinson et al. 2012, Newman et al. 2012, Shirk et al. 2012), insufficient attention has been paid to assessing the practical methodologies that identify and prioritize the key success factors capable of informing and promoting both resiliency and scaling of these networks.

One emergent approach to scaling networks in the field of public participation in science research is the creation of regional alliances: local organizations and individuals have the opportunity to host citizen science programs and scale them across regions by forming multi-partner alliances for a common purpose. These focused local activities can turn into larger orchestrated initiatives that serve both science and community development (Cooper et al. 2007, Dickinson et al. 2012). Existing data aggregation

platforms (e.g. USA-NPN, iNaturalist) can be used to activate these regional collaborative alliances to achieve what is often challenging for large–scale contributory projects. Collaborative alliances may be better positioned to recruit and retain active volunteers across geographic areas, address observer variability and data quality, and foster community-level involvement and activities – challenges which are often cited for centralized citizen science projects (Chu et al. 2012, Cooper et al. 2012). This is the first study I am aware of that specifically focuses on illustrating how to initiate these alliances, assess the outcomes of these collaborative efforts and understand which organizations might be best suited to catalyze or host generative networks.

This chapter is framed as a case study that seeks to identify some foundational principles drawn from my direct experience conceiving of and launching a successful regional community-science network. I have outlined in a process model the specific steps necessary to enable both national organizations (top-down) and local organizations or individuals (bottom-up) to conceive, activate and launch regional community science networks through a large-scale data aggregation platform. I have examined how different organizational attributes affect network node activity (volume of observers and observations) and diffusion (impact of project on larger community) in different ways for each node (organization). I offer some common attributes, tools and tactics shared by some of the highest performing nodes in the network, which could prove foundational to future analyses of community science network formation and scale. Overall, my intention is that this descriptive study will provide insight into how large-scale contributory citizen science initiatives can scale in a regional context, diffuse innovation in meaningful ways and ultimately become sustainable community-science networks.

Why Networks Matter

Ours is an age of networks. Networks are considered to be any group or system of interconnected parts (people or things). Networks consist of nodes (the part of a network, a point of intersection), links (the connections or associations between the nodes), grounds (the background support for the parts, typically made up of other networks) and hubs (nodes of a network that have a disproportionate amount of control over other parts, even over other networks (Newman 2003, Vitale 2014). Innovations derived from healthy and vital networks are becoming increasingly utilized across disciplines. Traditional divides, which have long existed between sectors such as business, medicine, science and education, are giving way to interdisciplinary initiatives that promote new paradigms (Bradshaw & Beckoff 2001, McBride et al. 2011).

As systems knowledge becomes increasingly central to organizational transformation and scalability, the role and purpose of networks (and network theory) is becoming increasingly important (Newman 2003). Technology is driving new and powerful collaborations across disciplines because it facilitates direct and simple methods of data gathering that can enable the general public to work with scientific professionals. Big data is now the norm and multi-partner networks are forming to create datasets and initiatives capable of addressing problems of rapid global change (Hampton et al. 2013, Newman 2010).

The typology of networks is still an emergent field despite the digitization of significant amounts of data that began nearly two decades ago and enabled researchers to begin speculating on network structure and scalability (Barabasi et al. 1999). The primary literature around networks in ecology, however, typically emphasizes the

mathematical properties of network theory (Leskovec 2008) and pays little attention to macrosocial issues (Bradshaw & Beckoff 2001) and specific microstructural explanations of network behavior (Kitts 1999). The lack of empirical evidence and replicable process models that describe how networks form, function and sustain themselves hinders the advancement of participatory research in ecology.

Citizen science and community science as emergent network movements

Historically, research that has deployed non-scientists in large-scale ecological projects has largely utilized a contributory model, with citizens acting as "sensors" collecting data for a scientist-led project (Dickinson & Bonney 2012). Though this model of participation is still relevant and practical for many data collection efforts, an effective development from it is a more "collaborative" one in which the research is co-developed between scientists, partner organizations and participants. In this more collaborative model, outcomes such as participant engagement and community development are intentionally prioritized (Dickinson & Bonney 2012, Fitzpatrick 2012).

In natural resource stewardship programs, for example, regional alliances are often formed to enhance collaboration for a common purpose (Belaire et al. 2011). This increased collaboration is cited to improve environmental, social and community-level outcomes (Purcell et al. 2012, Wondolleck & Yaffe 2000). Forming regional citizen science networks to enhance collaboration and deepen associated outcomes for large-scale citizen science research efforts, while less examined, has much potential as an effective approach. Community science, a term which perhaps best describes this model of collaborative participatory engagement, is one of many progressive, socially inspired

movements currently emerging in ecology.

Assessment needs for citizen and community-science

Some community science networks are robust and succeed in scaling, but many do not (Druschke & Seltzer 2012). Those attempting to launch these networks need to better understand what determines success. As suggested by Bonney et al. (2009), a robust network fosters long-term community-level involvement and activities, promotes environmental citizenship (Berkowitz et al. 2005) and ecological and civics literacy, engages under-represented audiences, makes use of appropriate cyber infrastructure, ensures projects' financial stability, and effectively disseminates results (Kransy & Tidball 2009). There is considerable research to support the value of community science initiatives (Sullivan et al. 2009, Delaney et al. 2008, Paulos et al. 2008) so exploring the details of actual network creation and maintenance is a necessary next step for research.

Best management practices and assessment methodologies proposed in community and citizen science typically focus on qualities such as project design, participant interaction, training and educational resources, data collection/validation, assessment of impacts, and sustainability (Dickinson et al. 2012). The macrostructural properties and organizational attributes that are foundational to the design and management of effective projects and associated technologies, however, are far less examined (Wiggins & Crowston 2011).

Organizations have varying capacities to catalyze and support networked initiatives based on foundational factors such as operational budgets, staff bandwidth

and local constituencies. With limited resources as the norm for most education, science and nature-based organizations, determining whether they are strategically positioned to build and scale up a citizen science initiative is critical. To evaluate strategic position, an organization first needs to know what factors contribute to a network's ability to be robust, resilient and efficacious. Empirical research is needed to elucidate the specific techniques and strategies required to activate and sustain a robust regional citizen science network effectively, as well as what the outcomes of these efforts are, and which organizations are best suited to catalyze or participate in these collaborative networks.

Carrying out the kinds of comprehensive, longitudinal studies necessary to answer some of these questions around the efficacy of collaborative alliances and network scalability is challenging – especially when the traditional divides between the natural and social sciences still persist. Real world case-studies and replicable process models can illustrate successful techniques and methodologies and perhaps provide the kind of insight needed to create more standardized research across scales and disciplines. This case study examines the practical and theoretical components of forming a viable community science network through the lens of establishing a phenology-monitoring network across a region.

Case Study Background

The rising interest in phenology monitoring makes it an effective lens on one of global change's most significant inquiries: ascertaining how plants and animals are responding to climate change at a regional, continental, and global scale. Phenology observation programs exist in many countries as a means of documenting plant and

animal response to climate. Many of these programs engage citizen scientists in creating and submitting reports in an attempt to amass observations at the scales and densities necessary to support rigorous research (Koch 2010, Sequeira et al. 2014, Schmeller et al. 2009). Programs such as FrogWatch USA (www.frogwatch.org), eBird (www.ebird.org), and Project BudBurst (www.budburst.org) collect, store, and share observations of plant or animal phenology collected by citizen scientists in various ways.

One such program, *Nature's Notebook* (www.nn.usanpn.org), managed by the USA National Phenology Network (USA-NPN), currently engages thousands of scientists and volunteers in documenting phenological stages across the country. USA-NPN describes their mission and function as providing a hierarchical, national monitoring framework that enables other organizations to leverage the capacity of the network for their own applications - minimizing investment and duplication of effort - while promoting interoperability (the ability to be used reciprocally). Network participants leverage several tools and services offered by the USA-NPN, including standardized monitoring protocols, long-term data maintenance and archive via the National Phenology Database (NPDb) maintained by the USA-NPN, and all of the outreach and training materials offered specific to *Nature's Notebook*, their observation and volunteer engagement platform.

At the outset, USA-NPN targeted individual observers primarily, but quickly began to accelerate models of group engagement to encourage participation among members of established volunteer groups, agencies, and national observation networks already monitoring biotic or abiotic parameters. Many of these developments were

sparked by observers themselves requesting increased functionality of the observation platform and database. USA-NPN was set up effectively to respond to these requests and augment them through staff expertise and cross-collaboration. Hence, the most rapidly growing segment of *Nature's Notebook* observers now participates as part of a locally or regionally organized group. Many organizations, including nature centers, arboreta, schools and colleges, Master Gardener and Master Naturalist chapters, and land trusts utilize *Nature's Notebook* as a mechanism to help meet their research, education and outreach programming goals.

In 2012, USA-NPN conducted a basic, preliminary analysis to determine whether the group model of participation (which they call Local Phenology Projects) was outperforming individual participation in number and "quality" of observations. Overall, they found that individuals who participate in *Nature's Notebook* as a part of a Local Phenology Project (LPP) are more likely to remain active in the program beyond the first year and submit higher-quality data than those who participate in *Nature's Notebook* independently (USA-NPN NCO 2012). Suggested explanations for greater engagement include 1) the burden to collect and submit data is reduced at the individual level because data collection is typically distributed across multiple observers, 2) participants have the support of other group members, camaraderie and social interaction, which may encourage continued participation and 3) participants experience face-to-face trainings and direct interaction with scientists and research/education staff at the hosting institution (USA-NPN NCO 2012). However, to date, only this basic inquiry has addressed differences in group versus individual performance, and variables that likely affect differences among the group model (e.g., institutional commitment,

trainings, social opportunities) have not been investigated. There are currently more than 300 different LPP's within the USA-NPN network. In addition, LPP's have begun to network across regions, which adds yet another layer of inquiry possible between singular LPP's and Regional Phenology Projects (RPP). There are approximately 15 projects (subsuming over 100 LPPs), that now have a regional multi-partner approach within the USA-NPN national network.

The New York Phenology Project (NYPP): launching a regional, networked LPP

In 2012, I conceived and launched NYPP, as one of the first regional networks that utilized the large-scale national citizen science platform managed by USA-NPN to generate an ecologically significant body of data. In 2017, NYPP collected 12% of the national phenology dataset and is considered by USA-NPN to be one of the best performing phenology data contributors in the country. The data collected by this network is currently being used in a comprehensive study comparing phenological change across two centuries (see Chapter 5).

NYPP was the first network created by the non-profit organization I also founded called Community Greenways Collaborative (CGC). CGC served as the "catalyst entity" to galvanize the initial pilot. I use the term catalyst entity to represent *the original initiator and accelerator of an initiative*. Once the catalyst entity (often an individual, but could be an institution, or even a coalition of institutions) performs the essential function of incubating the initiative and linking the first nodes of the network, it simply becomes another node in that network. At the start, however, catalyst entities are essential to successful network formation. They do the work; they convince, cajole and

collaborate to help a variety of stakeholders visualize what a successful network could accomplish for each of them. The process requires extensive preparation and planning. Trying to scale a network without proper strategy or analysis is not just foolhardy for the project itself, it is a disservice to the communities who have been called to participate. An incomplete initiative can have an unintended and opposite effect: it can dishearten passionate individuals who feel they wasted valuable time and could engender a future reluctance to be involved in any efforts on behalf of the environment or the science community as a whole.

CGC currently supports an array of phenology trails and sites established at various types of organizations such as nature centers, research stations and educational institutions (Figure 4.1). NYPP grew from a single location (my own home) with one observer to a statewide alliance of over 30 sites with over 250 active observers. The diversity within the alliance is significant, from The New York Botanical Garden and Gateway National Recreation Area (the largest urban national park in the US) to the Cary Institute for Ecosystem Studies and Brooklyn's historic Greenwood Cemetery. As a community-science initiative investigating changing plant and pollinator phenology across an urban to rural gradient in the New York region, NYPP's mission is to educate and engage the public while collecting data that are useful for detecting broad scale patterns in the natural world. Many of the participating organizations dedicate staff time (or in a few cases have "volunteer phenology trail coordinators") to either collect data or to coordinate data collection from citizen scientists on a weekly basis. These staff also oversee the upkeep of a marked trail/site for citizen scientists, volunteers and students to visit and utilize, whether regularly or intermittently. These activities and interactions

between organizational staff and the public around launching phenology trails and gathering data also stimulates the diffusion of innovative projects and initiatives.

Diffusion of innovation

Although NYPP's main mission is to collect phenology data, the organizations that participate often set up other types of programs during the adoption process that continue to prosper (even if phenology data collection efforts wane). This concept of novel or unexpected ideas, projects or collaborations spreading out from channels of social interaction from a point of singular concentration to a wider, more distributed network of individuals and organizations, is called "diffusion" (Rogers 2004).

In exploring examples of diffusion, we observed two different categories that are important to distinguish when measuring impact. The first category encompasses diffusion that is more related to internal capacity building, where new ideas and projects create more opportunity inside the organization. For example, one NYPP node, the New York Botanical Garden, created a "train the trainer" program so that almost all of the phenology-related trainings are run by experienced volunteers (who take new members out in the field one-on-one in addition to running the formal training sessions), built a children's pollinator garden as a new phenology monitoring site, created an internship program for teens to be "explainers" who could introduce children to the concept of phenology monitoring, and created a young researchers program to engage high school students in phenology research projects using their own data.

Second, some diffusion is more related to external capacity building where creating partnerships extends the work outside of the organization to broaden impact. An

example of this type of diffusion happened at Gateway National Recreation Area, another NYPP node in the NYC area. While this node was not able to get a consistent community science phenology monitoring program established, the process of hosting the initial workshops to train staff, local teachers and community members (in phenology and pollinator monitoring and restoration), led to the formation of new and productive partnerships. For example, this node partnered with CGC, the National Wildlife Federation and the Greenbelt Native Plant Center to launch Growing a Wild NYC (New York City) an initiative to bring students from underserved classrooms to Gateway to collect seeds from pollinator plants in the Fall and grow them in their classrooms to then plant on site in Spring in areas where invasive species were removed. This initiative engaged 8 different community partners that are all now connected, with some of them working on new projects together. We describe these two examples of diffusion to illustrate that project impact must be evaluated with nuanced attention – not all metrics of scale can be quantified.

Methods

The evaluation methodology described here layers principles and elements derived from Social Network Analysis, Organizational Analysis, as well as emergent frameworks to begin to assess and generate hypotheses about which organizational attributes, tools and tactics can predict network activity and encourage diffusion. I have evaluated NYPP both as a practitioner (the catalyst entity), and researcher in order to incorporate my direct experience with building and managing this network, and to generate further hypotheses about the dynamics and agents operating within and

influencing the network for future research.

To build the process model, I reviewed my notes, emails, start-up documents, spreadsheets and presentations to outline the pre-establishment assessment portion of the model. To implement the first steps of the post-establishment assessment, I conducted a series of interviews with a subset of the NYPP site leaders (representing 9 organizations) to begin to identify functioning nodes and categories of actual content diffusion, to determine organizational connections and to develop categories of inquiry that can help determine the organizational attributes and tactics that lead to node success. I compared number of observers, number of observations, the relative size of the organization and certain aspects of institutional commitment and project management, namely whether or not the program had a dedicated paid staff member devoted to the project, and broadly what their strategy of volunteer engagement was to see if there were any general patterns of predictability related to those specific variables. This preliminary examination of the network outcomes (the first steps of the post-establishment assessment portion of the process model) leverages quantitative and qualitative observations as well as summary data to build an understanding of NYPP's network experience so that it may be improved, iterated and replicated in other geographical regions or disciplines in the future.

The purpose of this preliminary inquiry was to generate enough information to outline key elements of node and subsequent network success, propose areas of further inquiry, and develop some assessment tools (such as a survey) that would aid in a more comprehensive future quantitative and qualitative evaluation of network success. My intent is that these simple tools and methodologies for shaping and assessing networks

can aid other organizations/individuals in both practice and research as they attempt to scale community-science monitoring programs and other social participatory research movements.

Results

From inception to impact:
A process model for establishing and evaluating
regional community-science initiatives

The process model outlined below is intended as a guide for how a catalyst entity or a national citizen science platform might utilize a large-scale data aggregation platform as the initial activation mechanism for a regional network, how to assess which organizations have the capacity to join and sustain the network (pre-establishment steps) and how to evaluate the formed network (post-establishment steps). This model illustrates the journey from inception to impact that the NYPP network has undergone (Figure 4.2).

Pre-establishment Steps (Conceiving and Launching):

Step 1: Map. Before the launch of a community science network is possible, the catalyst entity must develop a basic map of the landscape of potential stakeholders, allies and competing initiatives (to avoid redundancy and unnecessary conflicts). By determining who and where they are and by defining their relationship to the work of the national platform, we can begin to see the most promising regions (and content areas) with the best chance to scale a network and anticipate the potential for content diffusion.

I categorized the institutions by type (e.g. nature preserves, research institutions, botanical gardens, environmental education centers, state and national parks, etc.) and then mapped the most promising regions (e.g., those areas where organizations were already in relationship with one another, had common goals/needs or were in close proximity or had prior experience with the primary content or related content). Using a geographical map and defining the necessary assets, for example, I outlined the most promising sub-region to launch a pilot program. In my case, I identified the New York City through Mid Hudson Valley region as the most promising sub-region to launch a pilot because it had a high concentration of potential sites in a general location that afforded me some ease of ability to be physically present to help set up the initial sites.

Step 2. Design. In the design phase, the catalyst entity begins to evaluate and identify the organizations that offer the highest potential to support and grow a network. Evaluating attributes such as an organizations' mission alignment with the project, prior experience with the activity, brand recognition, and resources for institutional commitment can help the catalyst entity anticipate who will most likely support a pilot project and help incubate a vibrant network of activity. There are only so many organizations that can be engaged at one time, so this gathering of detailed information about which ones are the best fit for the pilot is critical to outlining the specific design of the project and planning the overall strategy that will be used to subsequently engage the organizations with a proposal. While it is difficult to predict what kind of diffusion is possible, it is easier to anticipate what content areas lend themselves to diffusion. I had, for example, tested the concept of "phenology trails" or phenology monitoring programs

in another location (Portland, Oregon) prior to launching NYPP and so had some prior experience determining the utility and potential impact (beyond just the data collection) of the Nature's Notebook observation platform with diverse communities of observers (Fuccillo et al. 2015). Therefore, I had enough prior knowledge to outline the categories of possible content diffusion around the work of the national platform and to come up with a working list of example organizations in my target area that might support and amplify these content areas in addition to successfully meeting the main objective of the program (to collect phenology data).

During the design stage for NYPP, I discovered that The New York Botanical Garden (NYBG) had a prior phenology-monitoring program in operation. Though NYBG's current program appeared to be successful, it was operating solely as a site-specific project and had limited dialogue about phenology with other institutions. NYPP's initial design outlined how the possibility of collaboration with this respected brand could leverage their expertise. Specifically, we evaluated their species-monitoring list to help us draft the initial species list that we planned to use to engage the organizations we were identifying as the best fit for the pilot. By having this level of detail organized in advance, the pilot organizations could actually visualize how they would participate by thinking about which species they would tag on their new phenology trail. If no such prior effort exists, it would still be important to determine specific draft lists to similarly allow potential participants to visualize their participation.

A catalyst entity likely has a broad mission or strategy in mind before even engaging in Step 1. However, the specific design and strategy is best developed when the catalyst entity has working knowledge of what the possible pilot organizations will

respond most favorably to. No strategy can fully anticipate preferences or events that will influence the eventual network development (positive or negative), but a design plan that includes a detailed evaluation of the actual organizations that might comprise the pilot will prepare the catalyst entity to offer a compelling approach when moving towards Step 3: the process of engagement.

Step 3. Engage. After thoughtfully and thoroughly completing steps 1 and 2, the catalyst entity must commence the challenging, direct work of engaging organizations about the possibility of participation in a pilot project. Key to this step is for the catalyst entity to deeply listen to the target organization and be sure that their mission and strategy aligns with the work of the project. Networks are catalyzed by a shared belief in what is relevant and achievable through collaboration. As the catalyst entity stimulates dialogue with an organization, it becomes easier to invite that organization into like-minded discussions with other stakeholders. As stakeholders connect, debate and collaborate around a shared strategic rationale for building partner-alliances across a given region, new approaches and possibilities surface; as organizations identify shared challenges, they are incented to propose and pursue innovative solutions that could potentially address those challenges.

Additionally, unanticipated events or opportunities can accelerate network formation. In the case of NYPP, for example, the work of steps 1-3 coincided with a timely opportunity. A Conservation Director of one of the nature centers I had identified as a possible pilot organization had just received a grant to bring together a small group of environmental research and education centers to explore the possibility of a regional

environmental alliance. The Director's process of visioning an alliance aligned with my own. We had some overlap on the regional focus and even which organizations we wished to engage. We discussed the possibility of the phenology trails project as one of the core pilot projects that could catalyze this new collaboration. We (CGC) became co-founding members of this formal alliance (called EMMA, the Environmental Monitoring and Management Alliance) and CGC, as NYPP's catalyst entity, made a proposal that outlined in detail how the design and implementation process for phenology sites could work. While CGC illustrated what the project entailed, we ensured that there was ample room for collaboration and flexibility to adapt each project to the mission of each organization while simultaneously meeting the goals of the alliance. EMMA is still functional today and has been a valuable consortium for CGC to further propose, pilot and support new NYPP projects and strategies around regional phenology monitoring and environmental education.

The fortuitous timing illustrated an important point: when identifying a region to propose a project, it is essential to identify whether or not there are any regional alliances already in operation, or about to form, even if the content does not completely match the content one might be proposing. In many fields, this is called a "window of opportunity" and generally describes a period of time during which a particular action can be taken that will attain a certain desired outcome (Ashford et al. 2006, Sull & Wang 2005). My assessment of this window of opportunity was from a business perspective; would it save time and money to launch through this proposed alliance? Would I create unnecessary competition by launching the network independently? Would adoption of NYPP be more successful if the organizations involved were working together on more

than one project? I determined that it was most beneficial to launch simultaneously with this alliance. For catalyst entities in the "engage" phase, in the event that a window of opportunity like this one does not present itself, the process of bringing together the possible pilot organizations would still look much the same as the way we described here.

Step 4: Catalyze. Intentional activities and actions that foster increasingly robust network linkages generate new nodes of activity. Aggressively calling for necessary supports for training and resources is easier when projects are underway and opportunities are visible to stakeholders. Catalyzing action and creating common milestones enables the initiative/network to move faster and more responsively to opportunities. Particularly when coordinating activities with citizen scientists, the right events, assemblies and materials can produce significant and useful collaborations.

I catalyzed the pilot by helping each organization set up a project that was aligned with their organization. For example, if the main priority of the organization was environmental education, we made sure that the phenology trail was in a location that was easily accessed by school field trips. If the organization mainly wanted to participate to contribute to research and only monitor with staff, we set up staff training programs and placed the observation site in a location convenient for staff to monitor. Concurrently, we (myself and CGC staff) set up the NYPP website where we began to compile all of the resources used to establish and support the monitoring sites, and gave each organization a "home page" that had a description of their specific project, which species they monitored, etc. The website enabled each organization to see what other

organizations were doing to further coordinate efforts. We organized and implemented trainings in certain locations and invited nearby nodes to join to begin to get to know one another's programs and share resources/training opportunities. Once the pilot was successful, we began our work in new regions of New York (Long Island, and upstate New York, for example), applying Steps 1-4 to extend the NYPP network.

Step 5. Convene. Healthy networks seek dialogue and opportunities to share learning. Step 5 means occasionally convening members of the network to explore common interests and common challenges. These gatherings do more than provide forums for information distribution, they stimulate allegiance between nodes, excitement over new trends, as well as opportunities to innovate with those who share common bonds.

Intermittently as the pilot was running, CGC would present how the work was coming along so that the network had a chance to see itself. We asked for input and constantly refined species lists, protocols and implementation strategies. Meetings were held on a sub-regional level only due to geographic limitations and limitations in our own funding capacity to host a major event. To limit expenditures, we often utilized already existing meetings (e.g. quarterly meetings of the EMMA group, conferences, multi-partner workshops). We compiled feedback and sent summaries to the entire network, and outlined new projects and strategies based on those summaries. For example, because many of the groups in the network talked about wanting to incorporate more direct management projects around their phenology monitoring endeavors, we came up with a suite of options for management-tied projects (invasive species monitoring, "nectar calendars" for old field management, etc.). We presented these

options and sites adopted them (or did not adopt them) based on their specific goals and time constraints. We followed up at subsequent gatherings to explore how to support each other's endeavors.

Evaluating impact and evolving the network

It is difficult to know when to implement a post-establishment assessment. Networks do not behave like organizations. They constantly morph as nodes grow or shrink, as links quicken or atrophy without warning. Network leaders and network catalysts do not have the kind of authority that a leader in hierarchical organizations do. They cannot demand a comprehensive evaluation without engaging the great majority of the network. Furthermore, how do we even know when the network is actually ready to be evaluated? How do we know when to call the network a network?

The volume and scale of NYPP's dataset, among other indications of network efficacy, indicated to me that the network was indeed a functional network - and ready for a preliminary analysis. I determined that NYPP began to demonstrate evidence of its functionality as a network when a series of conditions became commonplace: nodes (organizations) began interacting with each other; new nodes or sub-nodes spontaneously adopted the project; activities and innovations related to the citizen science project were diffused through communities; the network was capable of, and interested in, convening to explore next steps, and, most importantly, the continued functionality of the alliance did not depend on a single, central or authoritative node.

I derived these conditions for network functionality from my experience establishing and working with regional networks, as well as reviewing literature

primarily in the following fields: social science (Luke 2005), social ecological systems and citizen science (Bodin & Tengo 2012, Crain et al. 2014), adaptive and emergency management (Steelman et al. 2012), natural resource management (Wondolleck & Yaffe 2000), network sciences (Cumming et al 2010, Newman 2003) and social network analysis (Bodin & Crona 2009, Dickinson & Crain 2014). I propose that these above-mentioned conditions can apply to any community science network in order to demonstrate network functionality.

Post-Establishment Steps (Assessment and Improvement)

The catalyst entity (or any other entity that has a stake in the network), should undertake a post-establishment assessment when the network begins to demonstrate its efficacy as a network. A post-establishment assessment is critical to understanding a network's vitality because, as an evolving platform, the strengths and weaknesses of nodes and links signal emerging opportunities and challenges. In a post-establishment assessment, there are real data to work with and an established body of collaboration to assess. A thorough analysis that evaluates the full measure of the network is ideal, but sometimes (as described in this case study) it is necessary to begin with a preliminary analysis in order to design a more complete analysis. I have not undertaken a complete analysis at this time, but used the concepts outlined here (particularly steps 1 and 2) to generate preliminary findings that will aid in the development of a more complete future analysis. The steps below outline the general components of a post-establishment assessment.

Step 1: Assess. How are the nodes performing? What nodes or links are most productive? Where is the network strong and weak, decisive and timid? What are the categories of actual content diffusion around the work of the regional network or national platform? This step is similar to the first step of the pre-establishment assessment ("Mapping" the network) except now the catalyst entity is essentially taking stock of the actual outputs of each node and the network as a whole (instead of mapping the "potential" of each node).

Step 2. Evaluate. By identifying the organizations with strongest impact or influence, we can develop models that leverage regional institutional leadership to create greater community. By looking closely into the actual organizational connections and outputs one could infer more nuanced success factors related to network relationships and productivity. This step also mirrors the second step of the pre-establishment assessment (the "Design" phase) where the catalyst entity would determine the specific strengths or failures of each node to begin to create the study design needed to test hypotheses and preliminary findings.

Step 3. Test. A rich and varied approach to testing is key to validating network resilience. By testing links between organizational strategies and output with standardized qualitative and quantitative assessments, one could determine which activities, actions and strategies result in the greatest outputs of data and novel projects and ideas (diffusion).

Step 4: Synthesize. The varied elements of a network can never be fully synthesized—there are too many activities, perspectives and incongruent activities to integrate as each node pursues its mission and purpose. But network commonalities can be determined and shared values can be synthesized through careful examination. Every node in a network can and should be able to identify, in some manner, with the network's core mission. As a post –assessment looks to synthesize strands of activity, the network's strategic trajectory becomes more visible. The organizations attributes, their tools, tactics and outputs all contribute to a sense of the whole.

Step 5. Disseminate. As the post-assessment work is undertaken, it must be communicated throughout the network as an opportunity to consider the work of the whole. Where is our network going? How does the network reaffirm the common purpose and values that made the network in the first place? Dissemination is how the nodes in a network learn about the evolving activities that concern all or most of the organizations in the network. Periodically offering the entire network data that illustrates what various aspects of the network are doing stimulates dialogue and builds faith and allegiance amongst nodes and links.

Preliminary post establishment findings & key elements to evaluate network success

The organizations within the NYPP network demonstrate diversity in their approaches to monitoring and implementation; however, there are demonstrable success factors visible (and less visible) that underpin their ability to be, or transition toward becoming (or not), successful nodes within the network. Many nodes established

successful projects; some hit roadblocks that they could not overcome. This preliminary assessment of the network included some surprising and notable observations.

I had assumed, for example, that the larger the organization (budget, number of employees) or the bigger the scope of the phenological project (number of volunteers, number of staff dedicated to the project), the more data would be collected. I discovered that this was not necessarily the case. The size of the organization or project, for example, was not always related to volume of observations. While some of the largest organizations contributed a high volume of observations, there were multiple examples of much smaller organizations that contributed nearly the same amount. I learned that the number of observers did not necessarily predict the volume of observations generated either. Some nodes had only one or two observers and submitted more observations than nodes with more than ten observers.

Nodes with a higher number of observers had more observation conflict flags (where different observers reported both a "yes" and a "no" to a certain phenophase on the same day – indicating possible observation or data entry error). I noted too that the organizations with paid staff members who had some level of mandatory commitment to the phenology project and volunteer management (outlined in their job description) were more able to create and maintain a community of observers. The more successful organizations were not automatically the largest ones, but possessed a common feature: prior experience managing volunteers. The organizations that did engage volunteers in data collection efforts reported some common attributes that they linked to citizen science program success based on their communications with their volunteers.

The common attributes that were mentioned by 3 or more project leaders as important to them as well as to their volunteers (based on internal surveys or direct communication), included: field trainings (by staff or by other more experienced volunteer observers), social events such as meet ups and potlucks, intermittent email communication from the project leader that summarized notable phenology observations or gave information about what phenophases to be on alert for, helpful materials such as the NYPP species profile sheets, summaries of what their data were showing (or how it was being used) and the option of being able to use a mobile data collection app. The data collection app was also mentioned as a source of frustration however, as the early version of it did not work optimally and caused some participants to mistrust it even when the technological issues were resolved. Volunteer "perks" such as free membership, free parking, or special access to certain trails/locations were also cited by volunteers as being important to their sense of commitment to the project and being valued by the institution. Being part of a larger network (regional and national), having strategic goals such as standardized species lists, a focus on target issues (i.e., pollinator interactions, invasive species), and sharing materials and trainings with other organization were also cited as important. Almost all of the project leaders interviewed noted that they would like more interaction and open source sharing with other nodes in the network.

An additional discovery: it would appear that metrics of success are not always tied back to the initial goals of a given project. Several projects, for example, contributed very little actual phenology data to the network but demonstrated 'success" by their diffusion of innovation. They began pursuing the establishment of phenology

trails, but soon followed different paths including: creating materials and activities for a phenology curriculum developed and distributed for middle and high school classrooms; launching a series of evening lectures and community events that supported the organization's ongoing commitment to ecology; stimulating novel partnerships with other institutions around pollinator habitat restoration and more. I had anticipated successful diffusion in the design phase but was surprised by the extent of the new initiatives and engaging partnerships catalyzed by the attempted adoption of NYPP.

Related to that observation was still another one: the strength of relationship that organizations had with one another and with the catalyst entity appeared to have more impact on node activity and diffusion than the strength of connection to the data collection/platform organization. More organizational project leaders cited that they looked to other nodes in the network and to the catalyst entity for project management support, motivation and ideas than they did the national platform.

Key network elements:

I looked for a common set of principles, for key elements that might help organize a framework of inquiry, which we could use to begin to identify and then further test organizational capacity and project success. Thoughtful consideration of key elements contributing to network success can begin to help build a meaningful understanding of how, why, and when to scale focused, distributed initiatives. It also might illuminate which elements could be quantifiable predictors of performance and impact (however that is defined by the mission of the network) for this project specifically and broadly for other public participation in science research endeavors.

Based on my direct experiences with establishing nodes and managing networks, utilizing interviews and reviewing readily measurable dimensions of NYPP's participants (volume of observers/observations and examples of diffusion as indicators of success), I propose the following set of key characteristics that are important to evaluating node/overall network success: *Institutional Commitment, Strategic Goals & Governance, Volunteer Training, Communication Tools, Instructional Materials, Technology and Community-building* (Fig. 4.3). I discuss how these key elements relate to the preliminary findings in the discussion section below.

Discussion

While attention to any one of these individual key elements will not guarantee success, taken together they may significantly influence both the development and the long-term viability of a network. Further research will be required to unpack these elements in detail, identify their typologies and relationships to one another and explore their consistency with a larger sample size of interviewed organizations, but over the past 5 years I have developed direct experience as to how these indispensable elements might contribute to network node development and overall network success. The general concepts outlined in this section are based on my general observations and experience, as well as results of other studies (hence the use of present-tense language). However, where specified, I note direct observations derived from the preliminary inquiry described above.

Institutional Commitment: Perhaps the most influential attribute that affects node health, activity and diffusion, is a strong institutional commitment to approach the network as an expression of the organization's own mission and goals. When phenology observation, for example, is approached as a means to directly support the institution's mission, research, management, or outreach goals (as opposed to simply serving as a stand alone departmental activity), the likelihood increases that activity will be sustained over time. The level or type of institutional commitment can have direct effects on overall strategic goals and governance, as well as on specific elements of project success. Project design and management, for example, directly impact volunteer motivation and satisfaction (Bramston et al 2011, Bruyere & Rappe 2007, Dickinson et al. 2012), and are best supported by an organization's senior management. Examples in this case study, such as allocating paid staff to the project or offering "perks" (free membership, free parking etc.) to volunteers, is also a direct expression of institutional commitment to a project. The sanctioning of special privileges by the institution to its volunteers can often be interpreted by those volunteers as an institution's appreciation for them and as a demonstration of their belonging to that institution. I experienced directly (and frequently), for example, that such perks mattered more to volunteers than any standard letter of appreciation.

Strategic Goals & Governance: Organizations must take the time and effort to develop specific, clear and purposeful strategic goals to encourage agile leadership and effective management models. Strongly supporting the project will inevitably lead to faster integration of the work into the organization's broader activities and culture. The project

leaders we interviewed cited that sharing materials with other nodes, having a strategic focus for their project and feeling like they were part of a larger network were important. Governance is also key to the open management of network efforts (Conrad & Hilchey 2011). The articulation and management of the project must actively reflect (and be supported by) the organization's core governance principles. An organization might publicly claim "open source" as a core principle, but should they compromise that principle (refuse to share products, educational curriculum or training presentations with other nodes, for example, or bar members of other organizations from attending their trainings) the community will notice it immediately. I observed first hand two organizations that became more closed and insular as they increased regulatory governance around "ownership" of materials. In both cases, their programs lost participants.

Volunteer Training: While new and innovative training modules and curriculum are rapidly emerging, the steady presence of trained volunteers enhances the opportunity to accelerate data gathering and establish credibility for the public's role in scientific research**.** Effective training includes diverse options to meet different learner's needs. Field sessions with staff, field sessions with other volunteers, classroom training and/or webinars were all cited as valuable, with different constituents preferring different methods. Finding out which methods are preferred specifically by the volunteers involved can both improve the quality of the training and enhance the morale and engagement of the volunteers themselves.

Communication Tools: Clear and relevant communication is often cited as essential to harnessing the power of interdisciplinary scientific initiatives (McBride et al. 2011, Prysby & Super 2007). The communication and engagement tools that a network deploys to maintain interest, engagement and focus of the public are particularly important (Bingham 2006). Volunteer motivation and retention requires hands-on management expertise. One node with resources, facilities and clear mission can utterly fail, while another, lacking these obvious assets, somehow generates enormous activity and data collection. Clear communication (or the lack of it) can influence participant's overall experience with a project. Effective communication tools cited here included group emails or newsletters that gave participants a sense of what phenophases to watch for, summaries of phenophases in progress or interesting observations that volunteers had made. Observers also reported appreciating feedback on how and where their data were being used. Conveying the formal or informal analysis of the data collected vividly conveys to observers a sense of the utility and importance of their contribution.

Instructional materials: Accurate, informative and compelling instructional materials are invaluable to guiding and empowering volunteers (Druschke & Seltzer 2012). Ready access to these materials ensures that volunteers can maintain their own confidence in their ability to collect reliable data. The phenophase identification guides in this project were consistently cited as helping observers feel more confident in their observations.

Technology: Useable, relevant technology provides volunteers with the easy-to-use mobile tools they need to participate effectively and at-will (Newman et al. 2012). Using

innovative apps and simple algorithms on smart phones, ipads and hand held-devices of all kinds, citizens are empowered to make clear observations and contribute direct, reliable data. The mobile data collection app in this project was cited as a valuable option for some, particularly for the nodes who had adopted the project later in its trajectory. Unfortunately, the mobile app for this project had some major issues early on in the adoption process and many participants felt it was unreliable and did not want to try using it again after it failed initially—a clear indication of how the lack of reliable technology can have a negative impact on a project's overall success. Technological aids should be beta tested with a small group of more committed or tech-savvy participants before being distributed for broader use.

Community-building: Attention paid to stimulating community and belonging to the project and its purpose increases dedication, commitment and longevity of volunteer engagement (Bruyere & Rappe 2007). Learning is social and is often best accomplished through intentionally designed opportunities for people to build relationships. Potlucks, volunteer appreciation days and other types of intentional events were cited here as important to volunteer satisfaction and engagement. Many of the volunteers and project leaders noted that they wished there were more opportunities to hold events, particularly across organizations. The reason is clear: people enjoy belonging to systems that provide them with the opportunity to get to know one another and share a common purpose.

Further areas of research

A more detailed look at these key elements as categories of inquiry will help guide further exploration of the preliminary findings reported above (Appendix B.1). We used these key elements to build a survey tool, which we intend to use to further test our preliminary findings in future areas of research (Appendix B.2). We also outlined the predictor and response variables that could be used to explore the influence of these key elements on network success in a standardized quantitative and qualitative analysis (Appendix B.3). Many more unexpected links and commonalities are likely to emerge from further research. For example; an evaluation that looks at indicators such as phenology observation outlier data can help assess which observation models have the highest data accuracy. Or, a true social network analysis and exploration of social capital would further build a qualitative understanding of what it means to be a part of the community-science network experience.

Conclusion

Ultimately, the value of flourishing community science networks goes well beyond aggregated data collection opportunities. The diffusion of innovation encourages a wider array of relevant data gathered, regional research activities and experimental initiatives undertaken, and even orchestrated community participation, engagement and education on a national scale. These networks can and will produce data that actively influences best management practices for other developing programs. Community science is moving into a growth phase where institutions are rapidly launching programs and attempting to scale across regions. It is important to determine which ones have the

best chance of making a significant, sustainable contribution to advancing both science research and community engagement. Given the limitation of financial and human resources to launch and sustain network projects, we need to stress-test new models and conduct additional research studies that will assess more deeply the organizational components of successful citizen science networks.

This chapter, as a case study built from the ground up and anchored with practical and hands-on steps, offers a model to enable individuals or organizations (catalyst entities) to conceive, plan, engage and launch a vibrant, successful community science network. I have attempted to illustrate the necessary steps, the unexpected successes and the strategic benefits of bringing new participants, material and methodologies to the burgeoning world of public participation in ecological monitoring. I have sought to bring useable insights to an emerging movement. Now is the moment to leverage the passions of the public in service of the important climate change work underway in the ecological community. Faced with steepening ecological challenges, it is time to bring multiple stakeholders to the table to work through vital ecological matters important to all of us. We must continue our research and inquiry into how networks form and scale around ecologically significant issues.

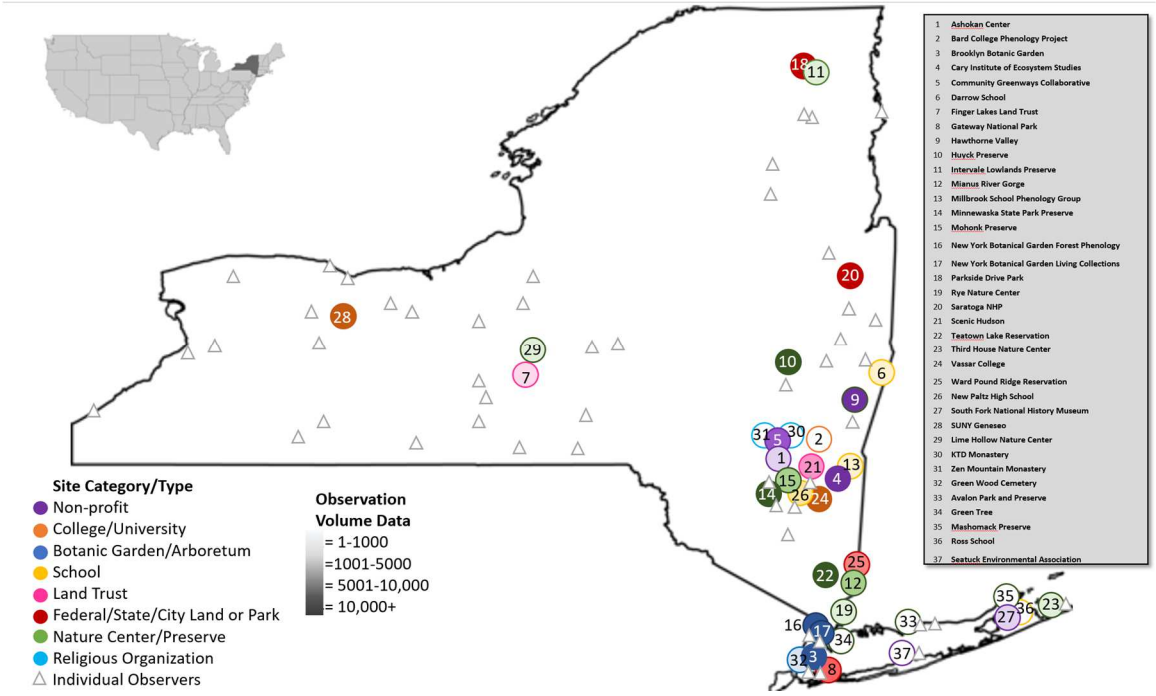


Figure. 4.1. Map of NYPP site with site type, active/non-active data collection efforts and gradient of volume of observations.

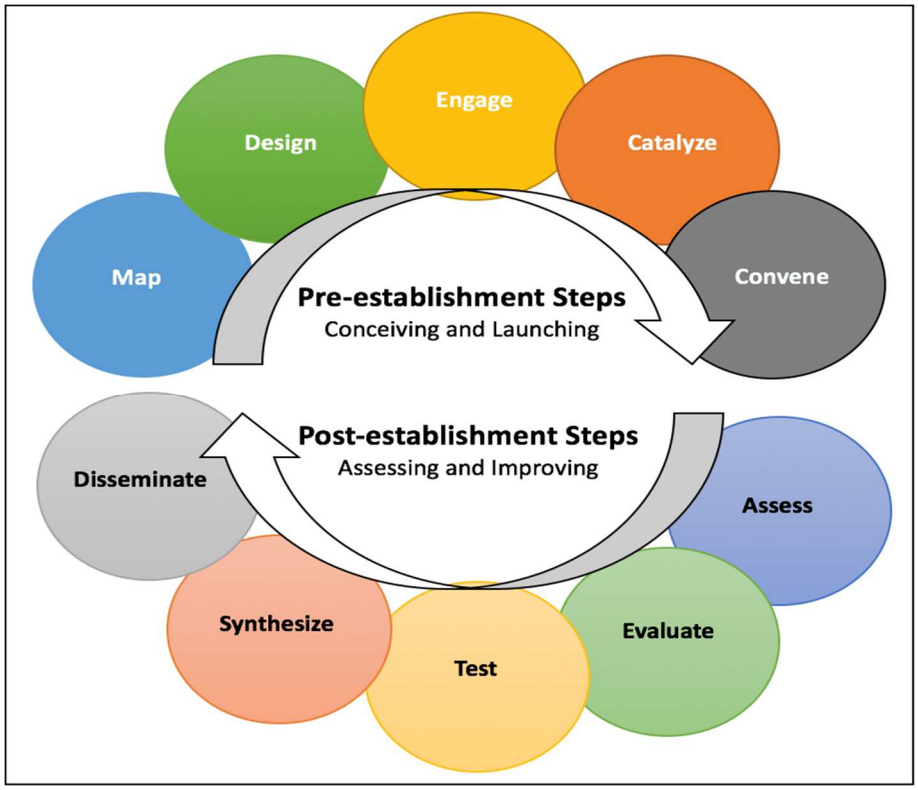


Figure 4.2. A conceptual framework model that can be utilized in both pre-establishment and post-establishment assessments by national platforms or local organizations that seek to evaluate or activate regional community science networks through large-scale data aggregation platforms.

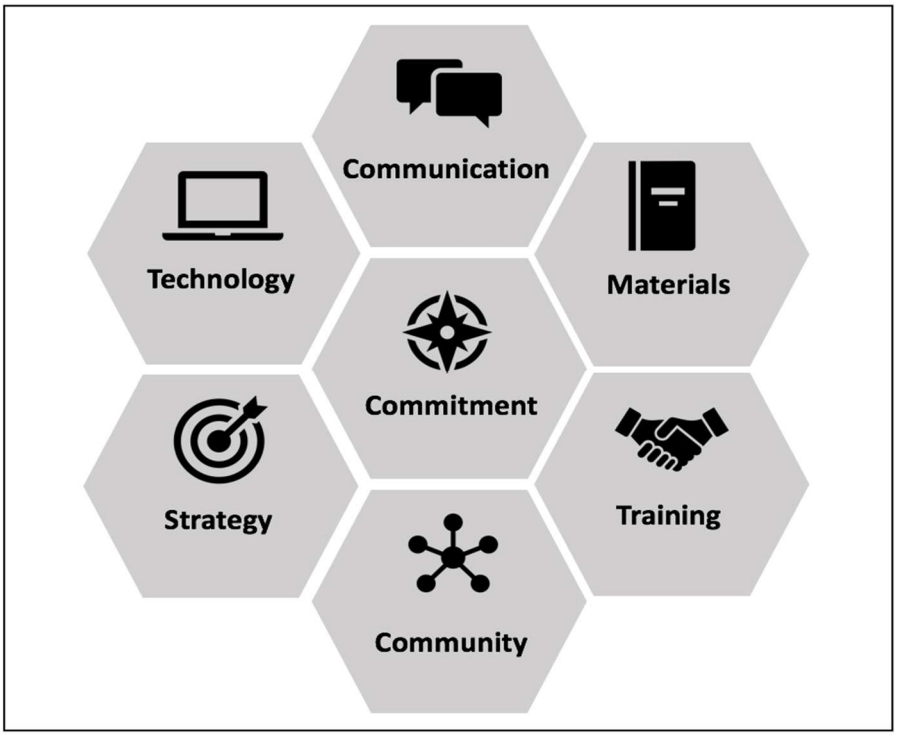


Figure 4.3 Key elements to evaluate individual node and overall network success

Chapter 5.

Two centuries of phenological change: An analysis of newly uncovered citizen-science network data across New York State

Introduction

The effect of climate change on the phenology—i.e., the timing of life cycle events—of organisms, is of primary ecological concern due to unknown cascading ecosystem impacts. Not all species are responding to climate change in the same ways: some species have shown no obvious change, while others are advancing or delaying the timing of their development (Ellwood et al. 2013, Parmesan & Yohe 2003, Root et al. 2003). Because phenology is a key life history trait for all organisms, phenological variation has consequences for individuals in the short term, as well as evolutionary impacts over time. Moreover, phenology is an important temporal factor in ecosystem functioning (Forrest & Miller-Rushing 2010, Wolkovich et al. 2014) and conservation (Morellato et al. 2016), and shifts in phenology can lead to asynchrony or mismatch between species (Edwards & Richardson 2004, Rafferty et al. 2015, Thackeray et al. 2016, Visser & Both 2005). This decoupling of species interactions, (e.g. plants and pollinators or animals and their food sources) has been reported in many systems (Both et al. 2009, Edwards and Richardson 2004, Memmott et al. 2007, Pearce-Higgins et al. 2005).

However, due to the nature of phenological research, many of these changes have been documented in local studies narrowly focused on a handful of species (see studies reviewed in Wolkovich et al. 2012). These studies are limited in their abilities to address community-level questions across spatial scales larger than single locations.

Changes have also been documented through broad-scale models or remote sensing, (Klosterman et al. 2014, Fortuna & Bascompte 2006, Melaas et al. 2016), but can be limited without ground-validated information to support finer-scale species change. The variability in phenological changes across studies, sites, and species makes it difficult to determine which species and interactions (e.g., between species and their food sources or key habitat conditions) deserve priority for further investigation. Meta-analyses (e.g., Diez et al. 2012, Wolkovich et al. 2012) can partially help overcome this limitation, but coherent large-scale, species-specific data sets (e.g., Primack et al. 2009) are best for addressing many questions relating to the ecological effects of changes in phenology. Unfortunately, these data sets are exceedingly rare.

The responsiveness of the phenology of some plants to warming temperatures is connected to plant performance—possibly because of ecological mismatches—based on studies at single locations (Cleland et al. 2012, Willis et al. 2008). But how similarly are the phenologies of individual species and communities changing across landscapes? The answer could have important ecological and conservation implications. Similarly, how might urban-rural gradients affect phenology-related ecological relationships and processes? Urbanization has recently resulted in steep urban-rural temperature and phenology gradients (because of the urban heat island effect), and these gradients occur over short distances (Bornstein 1968, Imhoff et al. 2010, Zhang et al. 2004). Significantly earlier reproductive phenology in urban areas could reproductively isolate urban populations of species. Earlier vegetation or insect phenology could provide early-season "islands" for migratory birds and insects (Tryjanowski et al. 2013). Coherent, large-scale, species-specific data sets can also allow more informed exploration of the

roles of other factors, such as seasonality or life form, to affect phenological response to climate change. For example, species with early-season vegetative or reproductive phenology might be subject to different selection pressures than species with later-season phenology (Lechowicz 1984, Rathcke & Lacey 1985), leading to different phenological responses to climate change; and these responses may vary across space, due to local adaptation, or with life form (i.e., forb, shrub, or tree) (Forrest & Miller-Rushing 2010, Keller et al. 2011, Miller-Rushing & Primack 2008).

Adequate long-term data sets at adequate scales, or modern data sets that can be paired with complementary historical data sets are scarce. Citizen science phenological observer networks capable of creating these long-term modern data sets existed in the past (Schwartz 2003), but largely stopped their work. However, they are now beginning to proliferate again and will increase in utility as their data sets grow. There are now large-scale national networks in Europe, Canada, Australia, China and the USA that deploy both citizens and scientists to collect phenological data. Citizen science can be beneficial for phenological data collection due to the high rate of collection, potential for large spatial scales, and social and educational benefits for the participants (Spellman & Mulder 2016). Citizen-science programs, or partnerships between scientists and non-scientists to conduct authentic scientific research, have become increasingly used as a source of phenological data (Beaubien & Hamann, 2011, Morisette et al. 2009, Wolkovich & Cleland 2011). The accuracy of phenological data produced through citizen-science programs has been variable when participants are required to identify plant species (MacKenzie 2017), but for general assessment of phenophases for identified plants has been shown to be highly accurate and useful (Fuccillo et al. 2015,

Crimmins et al. 2017). Remote sensing, which uses satellite imagery to calculate the timing of 'green-up,' also collects phenology data at large-scales (regional to global), but green-up data cannot differentiate individual species (Parmesan & Hanley 2015, Primack & Gallinat 2017). Herbarium specimens provide another good source of historical data (Calinger et al. 2013, Primack et al. 2004, Willis et al. 2017), but their records are generally poor for evaluating community-level changes across regions (Lavoie & Lachance 2006, Everill et al. 2014).

Our study utilizes a unique combination of a large-scale, community-level historical phenology dataset with a complementary recent (and ongoing) dataset. The historical dataset is from one of the oldest known examples of a historical network of institutions collecting phenological data through participatory science methods in the United States—a network throughout New York State during the years 1802-1878. We combine these data with observations from a modern network of institutions and individuals collecting data in much the same way across New York State from 2009-2017. The 150 historic and modern locations allow for a spread of sites across a fairly large geographic region with a range of highly urbanized sites to very rural sites (Fig. 1). There are 37 species in common between the datasets, with varying levels of representation. The combined dataset has among the oldest known phenology data in North America—older plant phenology data are known only from Europe (Chuine et al. 2004) and Asia (Aono & Kazui 2008).

We use this exceptional dataset to assess how the flowering and leaf phenology of a suite of plant species has changed over the last two hundred years, and whether those changes are associated with warming temperatures. Previous studies (Miller-

Rushing & Primack 2008, Primack et al 2004, Schwartz 1998) have found that late-winter and early-spring temperatures are strongly associated with flower and leaf phenology in the northeastern United States. We expect to find that the species in our dataset have a similar response to warming temperatures. We highlight species, or groups of species, that are responding most (and least) to changes in climate and whether variation among phenology is related to seasonality, life form, urban-rural classification or pollination syndrome. Based on previous studies, we anticipate that early-spring species (often subject to greater selection on phenology), and species growing in warmer areas will be particularly responsive to warming temperatures (Miller-Rushing & Primack 2008, Panchen et al. 2014, Wolkovich et al. 2014). Early-spring species are frequently subject to increased selection on phenology, though it is unclear why species in warmer temperate areas tend to shift phenology faster than species from higher latitudes (Wolkovich et al. 2014, McDonough MacKenzie 2017). We anticipate that species growing in urban locations will show more advanced phenology than their counterparts in rural areas over time (Tryjanowski et al. 2013) and that insect pollinated species will exhibit increased phenological responsiveness (advanced first flower dates) due to selection promoting earlier flowering to conserve pollinator mutualisms (Fitter & Fitter 2002, Calinger et al 2013). We also discuss the limitations of our data and make recommendations for future research on this and related phenology datasets.

Materials and Methods

Historical and contemporary phenology networks:

In 1825, the New York State Regents organized a network of academies to collect meteorological and phenological data. The effort was championed by Simeon Dewitt, the Surveyor General of New York and a well-known cartographer. The purpose, as we interpreted from the notes accompanying the data, was to find patterns in nature that could aid in agricultural decision-making (e.g., best time to plant certain crops, predicting bad winters, late frosts, etc.). In 1850, the effort was handed over to the Smithsonian Institution to oversee and archive. The Smithsonian subsequently set up other monitoring sites across the nation with varying degrees of success. The effort in New York remained strong until the Civil War, when data collection significantly waned; data collection stopped altogether in 1878.

This dataset was discovered in 2014 by Conrad Vispo of the Hawthorne Valley Farmscape and Ecology Program. He found a book that contained the data and description of the historical network and immediately recognized its historical value and potential contribution to the field of climate change research. He and his team then embarked on a mission to collect and assemble all of the books and archived material related to the project. He contacted us after finding that we were running a similar contemporary phenology monitoring program across New York State. Our two organizations collaborated to digitize and standardize the historical data with a dedicated team of ecologists, naturalists and cultural historians. All of the raw phenology data has

been digitized. Approximately 10 percent of the historic weather data has been digitized to date; these digitized data are included in this study.

Almost 200 years later, New York State is again home to a network of institutions and individuals collecting similar phenological data. The New York Phenology Project (NYPP), was founded as a community science initiative in 2012 to gather information about the timing of seasonal events and how the timing of those events might be affected by urbanization and a changing climate. We launched this effort with a small grant and eight initial pilot sites. It has since grown to include more than 30 sites across the state, some established by the founding organization and some by other organizations or individuals participating independently through NYPP and USA National Phenology Network (USA-NPN) websites. NYPP provides a list of core recommended species for participants to observe, but most organizations and individuals also monitor other species opportunistically (e.g., by monitoring species common at their sites, or species conveniently located along trails, etc.). The main purpose of NYPP is to collect phenology data, but many sites have educational programs and restoration efforts that function in association with NYPP (see Chapter 4 for more detail). Data collected by the historical phenology network and contemporary NYPP are available for public use as open source datasets, as are co-created curricula that teachers can use with students to get hands-on authentic science experience in their classrooms.

Phenology monitoring protocols:

The historic and contemporary datasets both contained the most amount of observations across their spatial range for the phenophases (life cycle stages), known as "breaking leaf bud" and "open flower." Fortunately, these two phenophases are considered to have high accuracy for volunteer collected phenology data for most species (Fuccillo et al. 2015) and so were chosen as the only two phenophases evaluated in this current study. Protocols for all contemporary data follow the USA-NPN protocols for plant phenology monitoring (Denny et al. 2014). Notes accompanying the data provide a written description of the historic phenology data protocols (Appendix C.2, which generally matched those of the USA-NPN). The protocol descriptions changed slightly between the 1825-1849 and 1850-1878 time periods; they became better defined and matched more precisely with modern phenology protocols in the latter time period. For example, the historic protocols describe leafing (or frondescence) as: When the buds first open and exhibit the green leaf…" and the modern protocols describe leafing (or "breaking leaf bud) as: "once a green tip is visible at the end of the bud...." In the historic protocols flowering is described as: "when the anther is first exhibited" and the modern protocols describe flowering (or "open flower") as: "flowers are considered open when the reproductive parts are visible…" The primary differences between historic and contemporary monitoring protocols were that in the earlier half of the historic time period (1825-1850), the protocols for vegetation were vaguer, using language such as: when flowers "blossom in their natural situation." The protocols were slightly more specific for agricultural species, which we have not included in this analysis. These earlier protocols did not mention leafing, as such there are limited data

for leafing in the historical dataset from that time span and they are not included in this analysis. The notes describe the "blank circulars issued for obtaining the data", in which two columns were provided for entering the dates of flowering of plants. One of these was designated for the dates of first appearance of blossoms, and the other for general flowering of the species. See Appendix C.2 for further details.

Weather monitoring protocols

The historic dataset included weather observations at each station (temperature and precipitation). The exact methodologies used to record daily mean temperature were slightly different across the historic time period, between the historic and modern time period and across the modern time period, (varying by year and location), but the general technique for both time periods was to average the minimum and maximum temperature of a given day. We used the monthly means that were provided in the historic summary publications of the data. Further details on historic weather observation protocols can be found in Appendix C.2.

Data preparation

The historic dataset was challenging to prepare as it was printed in multiple books, used scientific names that have since changed, and used phenophase descriptions (e.g., first flower and first leaf) that did not always precisely match current descriptions. The data were entered by hand. We consulted multiple botanical texts (e.g., Eaton 1836, Torrey 1843, Fernald 1950, Haines 2011) to match the historic species names (Latin binomials) with modern species names. Where there was inconsistent terminology in the

historic data, we calibrated historic phenophase descriptions to contemporary definitions. We checked the calibration with a phenology expert (Theresa M. Crimmins) at the USA-NPN. See Appendix C.1 for more detail on how the contemporary data were downloaded, organized and collated to prepare it for comparison.

Phenology data

Each phenology record consists of the date that the first leaf or flower of a species was observed at a particular location in a particular year. We refer to these records as First Leaf Date (FLD) and First Flower Date (FFD), and measure them according to the Day of Year (DOY) that they were observed. Our analysis includes contemporary data collected prior to the establishment of NYPP—e.g., at the New York Botanical Garden (starting in 2009), Saratoga National Historic Park (starting in 2010) (both current NYPP sites), and independent sites monitored by individuals. Thus, the contemporary data set spans up to eight years in some locations (2009-2017). There are more than 35 organizations and over 300 individuals collecting data in the complete contemporary data set. There were more than 100 locations in the complete historic meteorology and phenology data set, covering years 1802-1878. Very few locations collected data consistently across all years, but many had fairly regular and robust observations.

In our study, we used only data for species for which we had matching phenology observations for more than 3 years in each time period, and at least 10 observations total for FFD and FLD. These criteria are similar to those used in similar studies of regional multi-species phenology based on herbarium specimens (e.g.,

Calinger et al. 2013, Everill et al. 2014) and single site ground-based historical comparisons (Miller-Rushing & Primack 2008). The 909 species that lacked species or phenophase cross-over were removed. First leaf date for all forbs were also removed due to concerns about data accuracy—without precise definitions of FLD, as was the case in the historical data set, it is difficult to know what stage of emergence from the ground or leaf unfolding each observer identified as FLD. This process of removal resulted in a final dataset of 37 species (12 forbs, 12 shrubs, and 13 trees) at 150 locations (66 historical, and 88 contemporary locations, 35 of which are organized phenology monitoring programs and 53 of which are independent sites).

Because data were not continuous for the years 1802-2017, data were categorized into two time periods: historical 1802-1861 (sites with data 1862-1878 did not meet our criteria for inclusion in analysis) and contemporary 2009-2017. Exact locations of observations differed between historical and contemporary time periods (i.e., data did not represent repeat observations of the same individual plants over the entire period of study). Moreover, for any given year, observations of the same species at a site represented different individual plants, consistent with the protocols of the NYPP and USA-NPN. The data primarily includes observations of different individual plants across many locations in each year. Some of the same individual plants were observed in multiple years, but never in the same year per site. Therefore, observations of a species at a site were considered independent across time. The final data set provided spatial and temporal coverage for most species that is adequate and appropriate for our initial analysis of this exceptional data set (Figure 5.1).

Climate data

The historic data set included weather observations at stations (most often education-related academies and other related institutions) associated with many of the phenology data collection sites for the years. These are among the oldest and spatially extensive weather records known in the United States. Weather monitoring no longer occurs at the historic sites, but for most of them there are located near contemporary NOAA weather monitoring stations. The sites with the longest continuous data (those we used in our analyses) had mean monthly temperature data for 1826-1861. Protocols for historic weather data collection can be found in Appendix C.3.

We calculated Mean Spring Temperatures (MST) as the mean monthly temperatures for January-April (April is when most early-flowering and early-leafing species had flowered and leafed) following the example of Miller-Rushing & Primack 2008, Primack et al. 2004, and Schwartz 1998. Studies have found that finer temperature data (e.g., hourly or daily temperatures or growing degree days) only marginally improve explanatory power, and that the commonly used mean monthly or seasonal temperatures are adequate for most scientific studies, including studies of community-level data sets like the one in this study (Allen et al. 2014).

Historical climate data were not available for all locations in all years, so for all analyses that included MST as a variable, we used data from the location with the most complete data in our record: New York City. New York City had three historic and three contemporary weather stations with full data for both time periods for which we had phenology data (historic stations: Erasmus Hall, Fort Columbus, and Union Hall; contemporary stations: Central Park, LGA Airport, JFK Airport). To ensure that

variation in MST in New York City provided a reasonable approximation of variation in MST statewide, we tested the correlation among MST for three cities with historic and modern weather stations, one each from three of the current major Hardiness Zones in New York State (New York City = Zone 7, Kingston = Zone 6, Albany = Zone 5), for our period of study. MST at these locations were highly correlated ($r > 0.85$, $p < 0.001$ for all pairwise correlations; see Results for detailed correlation results).

Other explanatory variables:

Based on results of single-site studies or regional herbarium specimen-based studies, we included several categorical variables, in addition to MST, that likely contribute to changes in flowering and leaf phenology: Hardiness Zone (as a proxy for local climate and local adaptation), Seasonality, Life Form, and the Seasonality*Life Form interaction (Miller-Rushing & Primack 2008, Calinger et al. 2013, Wolkovich et al. 2014). We also separately analyzed changes in phenology between the two Time Periods—historical (1802-1861) and contemporary (2009-2017)— between urban and rural areas (Urban-Rural Classification); and between tree species with differing pollination syndromes (wind and insect) by season. Time Period and Urban-Rural Classification are both correlated with MST because of global warming and the urban heat island effect. Pollination syndrome differences were only comparable across time period for trees (forbs and shrubs in dataset are all insect pollinated) and were analyzed by season. We defined Seasonality as: early spring (March 1 to April 30, DOY 60-120), late spring (May 1 to June 1, DOY 121-152), or summer (June 2 – July 15, DOY 153-196); these categories reflect seasons with different selection pressures on phenology

and previously observed differences in phenological responses to climate change (Rathcke & Lacey 1985, Calinger et al. 2013, Wolkovich et al. 2014). US Department of Agriculture Hardiness Zones (Zones 4-7 occur in New York State) represented variation in climate (and associated local adaptation) across locations (Figure 5.1). Latitude and elevation are often used in analyses of phenology as proxies of spatial variation in climate, but in New York the influence of the Great Lakes and the Atlantic Ocean confound the relationships between climate and latitude and elevation, making Hardiness Zone a better proxy for spatial variation in climate, as reflected by maps of climate normals (Northeast Regional Climate Center, nrcc.cornell.edu). We used data from USDA Plants to assign species to Life Forms (i.e., forb, shrub/small tree, or tree). Urban-Rural Categories were assigned by compiling census data from both time periods and assigning each location an urban or rural status as it is described in the census data; each phenology observation was categorized as urban or rural based on the population at the time of observation. Pollination syndrome was classified for tree species as insect- or wind-pollinated based on literature review and the USDA Tree Atlas.

Statistical analyses

We began by assessing changes between historical and contemporary Time Periods. We used t-tests to assess a) changes in MST and b) changes in phenology (FFD and FLD) between the two Time Periods. The assessments of changes in phenology between Time Periods were conducted for all species combined, then individually, for species with at least 3 years of observations in each time period, and a total of ten observations per phenophase. To explore factors associated with variation in phenology

across the time periods, we pooled species across locations per phenophase (FFD or FLD) and analyzed by ANCOVA with MST (continuous) and categorical variables—Hardiness Zone (random), Seasonality (fixed), Life Form (fixed), and Seasonality*Life Form (fixed)—as explanatory variables. The historic time span for this ANCOVA covered 1826-1861 because those were the only historical years for which we had MST data. After testing for the influence that the explanatory variables had on variation in phenology (FFD and FLD), we explored the nature of the effects of each explanatory variable (identified *a priori*) individually through linear regression (for MST) and t-tests (for the categorical variables). To explore the influence of urbanization on species phenology, we ran t-tests on all species (combined and then individually for 12 of the most common species between the two datasets) classified by rural and urban locations. To explore the influence of pollination syndrome we pooled tree species across locations and analyzed by ANCOVA with MST (continuous) and categorical variables Seasonality (fixed), Pollination syndrome (fixed) as explanatory variables, and ran a t-test to explore changes between time periods for wind vs., insect pollinated trees by season. All data were evaluated with the statistical software package SAS, JMP v. 13.

Results

Changes in spring temperature 1802-2017

Mean Spring Temperature (MST) warmed substantially statewide between 1826 and 2017, as indicated by three measures. First, a time series in New York City revealed a relatively steady warming trend, beginning in 1880 (Figure 5.2), consistent with regional analyses of warming (Horton et al. 2014). Second, combined MST at three

locations (New York City, Kingston, and Albany) in different Hardiness Zones across the state warmed by an average of 1.0°C (1.8°F) between historical (1826-1861) and contemporary (2009-2017) time periods ($t = 1.94$; $N = 25$, $p = 0.028$, NYC= 3.96°C, Kingston =.33°C Albany = 1.13°C. Third, temperatures at three locations in New York City warmed by 2.5°C (4.6°F) between historical and contemporary time periods ($t = 4.81$, $N = 45$, $p < 0.001$); warming in the city was likely accelerated relative to other parts of the state because of the warming effects of urbanization. Despite the accelerated warming, interannual variation in MST in New York City—the site of our longest temperature time series—was representative of interannual variation elsewhere in the state: MST in New York City, Kingston, and Albany were highly correlated over the study period ($r > 0.91$, $N = 24$, $p < 0.001$ for all pairwise correlations; specifically, historical stations: Kingston-Albany $r = 0.853$, Kingston-NYC $r = 0.92$, NYC-Albany $r = 0.91$; contemporary stations: Kingston-Albany $r = 0.98$, Kingston-NYC $r = 0.98$, NYC-Albany $r = 0.98$).

Changes in spring phenology 1802-2017

With all species pooled across locations, FFD and FLD both advanced significantly from the historic (1802-1861) to contemporary (2009-2017) time periods, as indicated by t-tests (Fig. 3). FFD advanced 11.1 days ($t = 11.2$, $N = 2659$, $p < 0.001$), while FLD advanced 18.8 days ($t = 17.9$, $N = 2071$, $p < 0.0001$).

Changes in phenology of individual species

Individual species showed variation in average FFD and FLD difference across Time Periods, with most species showing earlier FFD and FLD in the contemporary time period. The full list of species-specific results can be found in Appendix C.4. We report here the summarized changes in FFD and FLD for 12 species commonly observed across Hardiness Zones (Tables 5.1 and 5.2), and categorized 12 similarly well-sampled ($n > 60$) species by Life Form to show changes in phenology visually (Figure.5. 4 and 5.5).

FFD for many species changed significantly between the historical and contemporary periods (Table 5.1, Figure 5.4). Approximately 85% of species evaluated showed advanced flowering in the contemporary period and approximately 60% of those were significant when pooled across hardiness zones ($p < 0.05$). For example, *Acer rubrum* (red maple), an important early season nectar source tree for many native bees, flowered 14 days earlier on average in the contemporary time period. *Cornus florida* (flowering dogwood, a small tree/shrub) and *Liriodendron tulipifera* (tulip tree, a tall canopy tree), both important late spring nectar sources, flowered 14 and 27 days earlier on average, respectively. *Asclepias syriaca*, (common milkweed), a key late season nectar source and the obligate genus host for the migratory monarch butterfly, flowered 13 days earlier on average. *Prunus serotina*, (black cherry, a small understory tree), was one of the only species with a robust sample size that did not show a significant change toward earlier FFD. *Erythronium americanum* (trout lily) and *Maianthemum canadense* (Canada mayflower), both early season spring ephemeral forbs, flowered 7 and 6 days earlier on average when pooled across Hardiness Zones.

For some species FFD changed differently in different Hardiness Zones. For example, *Acer saccharum* (sugar maple) flowered 8 and 9 days earlier in the modern period on average for Hardiness Zones 5 and 6, respectively, but flowered 18 days earlier in Hardiness Zone 7, the zone that comprises the more urban area of New York City and lower Westchester County. *Lindera benzoin*, (spicebush), one of the first early season nectar source shrubs for small native bees, showed a drastic difference across Hardiness Zones, flowering 7 and 8 days earlier in zones 5 and 6, but 27 days earlier in zone 7.

Individual species also showed variation in average FLD differences across time periods (Table 5.2, Figure 5.5). All of the species showed earlier FLD in the contemporary time period and approximately 80% of those were significant when pooled across hardiness zones ($p < 0.05$). For example, *Acer rubrum* (red maple), *Acer saccharum* (sugar maple), *Fraxinus americana* (white ash) and *Tilia americana* (basswood), all common tree species found in intermediate-mature northeastern forests, are all leafing out 13-14 days earlier in the modern time period. *Liriodendron tulipifera* (tulip tree) and *Quercus alba* (white oak) both shade-intolerant early succession species, are leafing out 26 and 28 days earlier on average in the modern time period.

Prunus serotina (black cherry), though, on average leafed out 14 days earlier in the modern time period was variable across hardiness zones, with earlier leaf out more pronounced in the modern time period in the higher latitude zones, opposite to what is expected with increased urban warming or global climate change. *Syringa vulgaris* (common lilac) also showed variability across hardiness zones, tending towards earlier leaf out in higher latitude zones, but leafed out 14 days earlier on average across

hardiness zones. *Lindera benzoin* (spicebush), a common understory forest shrub and the host species for spicebush swallowtail butterfly, showed the most dramatic changes, leafing out 27 days earlier on average, ranging from 18 days earlier now in the rural areas and decreasing with latitude and urbanization to 31 days ahead in the urban areas. With all species pooled and analyzed by hardiness zone (to account for spatial variation), there was a significant trend toward earlier leaf out in the modern time period (zones 5, 6 and 7: $p < 0.001$). Zone 4 has limited representation, particularly in the historic time period and does not show a significant trend in either direction.

Factors that explain variance in changes in spring phenology

Mean Spring Temperature, Seasonality, Life Form (for FFD), and Seasonality*Life Form explained significant ($p < 0.05$) amounts of variation in FFD and FLD, as determined by ANCOVA (Table 5.3).

Mean Spring Temperatures (MST) – FFD and FLD tended to advance as MST warmed, FFD by 3.2 days/°C and FLD by 3.0 days/°C (Figure 5.6). The relationships between FFD and MST for eight of the most commonly observed tree, shrub and forb species in our data set is shown in Figure 5.7. For all eight species warmer temperatures were associated with earlier FFDs, ranging from 2.4 days earlier/°C for *Erythronium americanum* (dogtooth violet) to 6.3 days earlier/°C for *Ulmus americana* (American elm) and *Acer rubrum* (Red maple).

Hardiness Zones – When species are categorized by Hardiness Zone, FFD tended to occur earlier in the contemporary time period for zones 5, 6, and 7 (zone 5: 12.25 days earlier, $t = 7.04$, $p < 0.001$; zone 6: 5.07 days earlier, $t = 2.57$, $p = 0.010$; zone 7:

9.99 days earlier, t = 4.99, p < 0.001), but not for Hardiness Zone 4, which had limited sample size in the contemporary time period and does not show a statistically significant change in FFD between the historic and contemporary time periods (Figure 5.8). Results for FLD followed a similar pattern—significantly earlier FLD in Hardiness Zones 5, 6, and 7 (zone 5: 18.27 days earlier, t = 10.74, p < 0.001; zone 6: 18.88 days earlier, t = 9.98, p <0.001; zone 7: 19.20 days earlier, t = 9.90, p < 0.001, but not in zone 4 (Figure 5.8).

Seasonality – For species with early- versus late-spring phenologies, FFD and FLD occurred earlier in the contemporary time period than they did in the historical time period, especially for early spring phenologies (Figure 5.9). FLD tended to advance more than FFD. For early-spring species FLD occurred 17.0 days earlier (t=13.80, p < 0.001) in the contemporary time period, whereas FFD occurred 9.7 days earlier in the contemporary time period than in the historical time period (t = 8.80, p < 0.001). For late-spring species FLD occurred 12.8 days earlier (t = 6.17, p < 0.001), whereas FFD occurred 4.3 days earlier (t = 4.38, p < 0.001). For summer species, FFD did not change significantly between time periods (t=0.47 p = 0.64) (Figure 5.9).

Life Form – FFD and FLD occurred significantly earlier in the contemporary compared to historical time period for shrubs/small trees (FFD 16.9 days earlier *(*t = *8.92*, p < *0.00*1), and FLD 16.4 days earlier –(*t =7.64, p < 0.001))* and trees (FFD 18.1 days earlier (11.22, p < *0.00*1), and FLD 19.9 days earlier *(t = 16.97, p < 0.001)*). (Fig. 10). In contrast, FFD for forbs occurred 4.4 days later in the contemporary period compared to the historic period (t = -2.71, p = *0.007)* (Figure 5.10). The trend toward later FFD for forbs appeared to be driven by two late-spring and summer species with

poor sampling in the contemporary time period; of the 12 forb species included in our data set, 10 had FFDs that occurred earlier in contemporary time period than they did in the historical time period (Figure 5.11).

Seasonality and Life Form Interaction – The interaction between Seasonality and Life Form shows that while FFD and FLD occurred earlier over time for most species, the FFDs of late-spring-flowering forbs and summer-flowering trees did not change substantially, or occurred later over time (Figure 5.12). Late-spring flowering trees showed the most significant change across time periods, occurring 21 days earlier on average. In general, however, the species with early-spring flowering and leaf out had the most consistent and least variable changes in FFD and FLD for all life forms, whereas the late spring time period was more variable for FFD and FLD over time (Figure 5.12). Statistical results for the interaction are shown in Table 5.4.

Factors that explore trends in changes in spring phenology

Urban-Rural Classification – FFD advanced by 8.8 days in rural areas between historical and modern time periods ($t = 5.26$, $p < 0.001$), compared to an advance of 10.4 days in urban areas ($t = 7.86$, $p < 0.001$) (Fig. 13). FLD advanced 16.8 days in rural areas ($t = 9.48$, $p < 0.001$), compared to a 21.0-day advance in urban areas ($t = 16.23$, $p < 0.001$) (Fig. 13). When individual species were analyzed separately, some species showed strong differences in how much FFD or FLD changed between urban and rural areas. For example, FFDs for *Acer rubrum, Liriodendron tulipifera and Syringa vulgaris* advanced more between time periods in urban areas than they did in rural areas (advanced 5, 18, and 4 days, respectively, faster in urban areas compared to rural areas)

(Table 5.5). *Acer saccharum and Ulmus americana* showed the opposite tendency; their FFDs advanced more in rural areas (2 and 6 days more, respectively). When analyzed by species, FLD also had variable trends across species (Table 5.6). FLDs for *Acer saccharum, Cornus florida, Liriodendron tulipifera and Quercus alba* all advanced more in urban areas (3, 2, 6, and 4 days earlier, respectively). FLDs for *Acer rubrum* and *Tilia americana* showed the opposite trend, and advanced more in rural areas (4 and 3 days earlier, respectively).

Pollination Syndrome – Mean Spring Temperature, Seasonality and Pollination Syndrome explained a significant amount of variation in FFD for trees as determined by ANCOVA (Table 7). FFD advanced by 10.1 days for early-spring wind pollinated tree species between historical and modern time periods ($t = 3.24$, $N=111$, $p < 0.0001$), compared to an advance of 14.81 days for early spring insect pollinated tree species ($t = 8.28$, $N=558$, $p < 0.0001$). FFD advanced 15.95 days for late-spring pollinated tree species ($t = 2.35$, $N=151$, $p < 0.0001$), compared to a 27.5-day advance for late-spring insect pollinated tree species ($t = 5.46$, $N=136$, $p < 0.001$) (Table 5.8).

Discussion

In this first exploration of an exceptional long-term (1802-2017), community-level phenology dataset that spans New York State, USA, interesting and significant patterns of phenological change over time have emerged. The dataset provides statewide phenology and temperature data that extend further back in time than any previously known dataset for the region, extending to years prior to or at the beginning of recent

human-caused global warming (Stocker et al. 2013). Most species are flowering and leafing earlier in recent years (2009-2017) than they did in the early 19th century (1802-1861). Plants are flowering 11 days earlier and leafing 18.8 days earlier—with some species flowering up to 27 days earlier and leafing up to 31 days earlier over that time period. Most of this change was driven by warming mean spring temperatures (MST) over that time; mean spring temperatures warmed by 1.0°C statewide (2.5°C in New York City) on average between the historical and contemporary periods. Seasonality, Life Form, and the interaction between Seasonality and Life Form explained variation in phenology among species. Changes in phenology also differed between urban and rural areas, with larger changes occurring in urban habitats, likely driven by warmer temperatures in those urban areas. Pollination syndrome also had differential effects across time period with insect pollinated trees flowering significantly earlier than wind pollinated trees when categorized by season.

These main results of earlier spring blooming and leaf-out in modern than historic times are consistent with previous studies (Cook et al. 2012). Our study significantly strengthens the evidence of this trend by covering a longer time period than is covered in previous work. The magnitude of phenological changes in New York (flowering and leafing on average 3-6 days/°C) appear to generally match those described by other studies in the Northeast region as well (Cook et al. 2008, Everill et al. 2014, Melaas et al 2016, Miller Rushing & Primack 2008, Morin et al 2009, Polgar et al 2014, White et al. 2014). However, New York phenology shows a particularly strong signal of change over time, likely due to the length of the time series in this particular dataset.

A striking result from our New York dataset is the high degree of variation among species and phenophases in the in the magnitude of change, some of which have not been shown by previous studies. For example—leaf out appears to be advancing much faster than flowering in our dataset and some species show changes between time periods of more than three weeks. This variation highlights the changes in interactions among species and ecosystem dynamics that may already be occurring. Many pollinators and herbivores, particularly those that rely on a small number of plants, are vulnerable to becoming mismatched with their food resources (Forrest 2015, Kharouba et al. 2015, Kudo & Ida 2013, Rafferty & Ives 2011). For example, here we found evidence of a potential mismatch based on the magnitude of change for the species *Lindera benzoin*, the obligate host of the spicebush swallow tail butterfly, which leafed out 27 days earlier on average in the contemporary time period. Another example is the particularly rapid advancement of early-season species, which has the potential to extend the flowering season and reduce the number of species flowering at any given time, possibly reducing resources available for species at particular times (Aldridge et al. 2011, Diez et al. 2012).

Additionally, the differences we found here in phenological change among life forms suggest that interactions between different canopy levels may change as well, possibly affecting species that compete for light to support early-season growth and photosynthesis, and those that rely on light in the understory during flowering (Hudson et al. 2017, Kudo et al. 2008, Sercu et al. 2017). Selection on phenology may drive the species most vulnerable to these mismatches with the canopy to advance phenology faster, but that could increase their vulnerability to late-season frosts (Augspurger 2013,

Inouye 2000). Our findings of distinct patterns of phenological responsiveness among life forms are a significant addition to the limited number of studies globally that have evaluated variations in phenological sensitivity at the functional group level (Keller et al. 2011, Miller-Rushing & Primack 2008).

Plants in urban areas also appear to be shifting phenology much faster than those in rural areas, likely driven by more rapid warming in urban areas (2.5°C warming in New York City compared to 1°C average statewide between historical and contemporary periods in this study). This pattern is already causing urban areas to become "islands" of early phenology (Zhang et al. 2004), and may further isolate urban populations from rural populations in the future. These islands could facilitate responses to climate change for migratory species (Tryjanowski et al. 2013), or could contribute to phenological mismatches as urban areas become increasingly disconnected from surrounding landscapes. Phenological reproductive isolation of urban populations could also facilitate evolution within these populations; speciation is already being seen in some urban populations (Yakub & Tiffin 2017).

Our study is the first we know of that has documented a difference in phenological responsiveness due to pollination syndrome with ground-collected historical data over a large geographic region. Insect-pollinated tree species showed a significantly greater phenological advancement than wind-pollinated ones in the contemporary time period by season (14.8 days for insect pollinated versus 10.1 days for wind pollinated early-spring flowering species and 27.5 days for insect pollinated versus 15.95 days for wind pollinated late spring flowering species). Temperature changes may have more of an effect on insect pollinated species across time due to selection

promoting earlier flowering time to conserve pollinator mutualisms (Fitter & Fitter 2002). Many trees and shrubs provide a large proportion of nectar for pollinators due to their size and abundance of flowers, particularly during the early spring season (Vaughn & Black 2006). Too much phenological sensitivity to temperature change (in trees and shrubs specifically) could therefore have dire consequences for pollinators if they are not responding synchronously.

For example, we characterized red maple as an insect pollinated tree species (though it also reproduces by wind pollination, it produces such abundant nectar that it is extremely important to pollinators). Red maple is the first major nectar plant of the spring season and both native pollinators and honeybees are highly dependent on this first flush of nectar. Our study found that red maple is flowering more than two weeks earlier on average in the contemporary time period and has a strong relationship to MST. Therefore, if this crucial nectar source species responds to warm temperatures in late winter/early spring and either pollinator species do not respond synchronously, or frost kills the initial flowers, local pollinator populations could be severely impacted by this one species alone.

Species that appear to be particularly sensitive to changes in spring temperatures may be able to serve as indicator species to help identify ecological dynamics that deserve investigative or conservation priority. Species that were and are relatively common in both urban, rural and wild locations may be able to illustrate these changes most effectively. These species include *Cornus florida* (flowering dogwood) which flowered more than 3.5 days/°C days earlier, *Acer rubrum* (red maple), which flowered more than 4.7 days/°C and *Ulmus americana* (American elm), which flowered 6.7

days/°C earlier in the contemporary period. Nonnative species that are sensitive to changes in temperature such as *Robinia psuedoacacia* (Black locust), which flowered and leafed out earlier in the contemporary time period, may have the ability to become increasingly invasive (Willis et al. 2010, Wolkovich et al. 2013).

Species with phenologies that do not appear to be responding to changes in temperature—e.g., late-spring forbs, may be particularly vulnerable to declining in abundance, potentially due to lack of plasticity or overall adaptability (Cleland et al. 2012, Willis et al. 2008,). First leaf date for many of the common tree species in our modern day second growth forests have advanced by about two weeks, with some such as *Quercus alba* (white oak) advancing by 3-4 weeks in most of its range. Together, these community-level and species-specific results will inform ecologists and resource managers who are exploring and managing the ecological and evolutionary impacts of non-synchronous phenological changes among organisms (Enquist et al. 2014, Morellato et al. 2016).

Limitations

Though these datasets are extensive and have provided solid evidence of phenological change over time, there are limitations that present challenges. The historic dataset is spotty in some locations (i.e., not continuous and more heavily sampled in some areas than others), and there is a large gap between 1861 and 2009, during which there was no statewide phenology program. Nonetheless, this dataset allows us to compare pre-industrial phenologies with modern ones. The amount of years covered between datasets is different for temperature and phenology and the historic locations

that reported weather and phenology observations in a given year vary. The locations that report in the contemporary period are not exactly the same locations as in the historical period, though there is overlap in general locations (e.g. Albany area, NYC area). Though we minimized the potential bias created by these issues by grouping species by hardiness zone, microclimate variation could be playing a role in species differences across time, especially when looking at the species-specific data, with their smaller datasets. The lack of exact protocol match between time periods could also be contributing to variance in the dataset. The earlier protocols for flowering for example were vaguer and did not specify to look for the reproductive parts of the flower as the latter historic time period and contemporary protocols do. As we digitize more of the historical data and find associated information, we plan to work to minimize these limitations (although we will not be able to completely remove them). Despite the limitations, our data appear to yield very useful results, as indicated by the broad agreement with patterns found at other locations in the region.

Conclusions and future research

Our data show a strong signal of phenological change in response to climate change across New York. Our data adds a critical piece to the growing literature describing phenological change: we add earlier (pre-1850s) and a broader spatial scale of community-level phenology data than exist from other floras. Previously comparable data were primarily available only from herbarium specimens, which have known sampling biases (Daru et al. 2018). Our data largely confirm patterns found in these earlier studies, but highlight the potential for mismatches and other changes in

interactions --such as shifts in plant-pollinator, plant-herbivore, or plant-plant relationships-- to occur not only locally, but also spatially—e.g., along urban-rural and other climate gradients. This spatial variation in phenological change could have implications for migratory species and herbivores with large ranges, and for the reproductive isolation of urban plant species populations, which could then facilitate evolution in those populations. We also identified species that might be used as indicators of changes in phenology and those that might be vulnerable to climate change. Our study will help researchers determine which species to include in their examinations of the ecological and evolutionary impacts of non-synchronous phenological changes among organisms.

There is much potential to use this dataset to expand on the research described here (see Appendix C.3). For example, the New York Phenology Project (and wider USA National Phenology Network (USA-NPN) have animal phenology data available to use in comparison with the historic NY dataset and will allow more direct study of the simultaneous changes in phenology of interacting plants and animals, such as plants and pollinators, especially as the modern dataset expands to include more species. Similarly, the historic and modern dataset have other phenophases available for comparison. For example, we can study changes in phenophases in other seasons, like autumn, which have been understudied relative to spring (Gallinat et al. 2015). Also, the climate and phenology data can be used to extend indices of climate and phenology back further in time than has been possible to date (Ault et al. 2015).

Last, we hope that this study and future work building on it facilitates the expansion of phenology networks and the discovery of more networks and remarkable

phenology-observing individuals from the past. Their data could provide much-needed insights to help us continue to grow our understanding of phenological changes and their consequences. By bringing the efforts of a historical network into a modern context we explicitly illustrate how organized long-term monitoring efforts can be valuable for ecological discovery. Interest generated by the compelling narrative of a historical citizen-science effort of this magnitude can be valuable in increasing public awareness of biological response to climate change, and how the public can contribute valuable data used by researchers to answer pressing ecological questions.

Chapter 5. Tables and Figures

Table 5.1. Changes in First Flower Date (FFD) between historical (H) (1826-1878) and contemporary (C) (2009-2017) time periods for 12 commonly observed species (n > 60 across zones, n>3 per time period, per zone), as indicated by t-test. Difference is given in days ± one standard error. Statistically significant ($p < 0.05$) p-values are highlighted in orange. Hardiness Zone 4 was omitted because most of these species did not occur frequently in that zone. Dashed lines indicate zones without adequate representation for comparison (n<3 per time period, per zone.

USDA Hardiness	All Zones		Zone 5	Zone 6	Zone 7
Species	Difference p-value	T statistic/ *n= (C, H)*	Difference p-value	Difference p-value	Difference p-value
Acer rubrum	14.90 ± 2.03 **<.0001**	7.36 (300, 104)	18.93 ± 3.28 **<.0001**	7.16 ± 3.47 **0.0419**	11.06 ± 4.06 **0.0072**
Acer saccharum	11.51 ± 2.09 **<.0001**	5.52 (83, 53)	8.14 ± 2.42 **0.0015**	9.45 ± 3.26 **0.0060**	18.43 ± 10.29 0.0850
Asclepias syriaca	12.95 ± 6.03 **0.0352**	2.15 (58, 17)	14.40±3.39 **0.0010**	1.32±4.65 0.7776	---
Cornus florida	13.59 ± 3.02 **<.0001**	4.49 (95, 37)	16.97 ± 8.11 **0.0269**	6.85 ± 4.35 0.1210	19.50 ± 4.28 **<.0001**
Erythronium americanum	6.76 ± 2.06 **0.0015**	3.28 (51, 47)	4.07 ± 2.40 0.1003	2.50 ± 2.74 0.3681	12.63 ± 7.76 0.1220
Lindera benzoin	11.73 ± 3.52 **0.0011**	3.33 (134, 18)	7.72 ± 8.94 0.3961	7.37 ± 3.02 **0.0185**	29.17 ± 10.50 **0.0070**
Liriodendron tulipifera	27.50 ± 5.03 **<.0001**	5.47 (116, 20)	22.08 ± 7.59 **0.0115**	18.03 ± 4.65 **0.0008**	25.36 ± 11.79 **0.0341**
Maianthemum canadense	6.18 ± 3.09 **0.0492**	2.00 (60, 14)	0.67 ± 4.62 0.8873	---	-2.92 ± 6.14 0.6474
Prunus serotina	3.14 ± 4.03 0.4369	0.78 (115, 12)	7.67 ± 6.24 0.2292	---	-2.62 ± 6.77 0.6995
Quercus alba	11.41 ± 4.38 **0.0116**	2.60 (52, 11)	13.83 ± 8.36 0.1100	5.00 ± 12.28 0.6960	17.08 ± 7.78 **0.0379**
Syringia vulgaris	11.22 ± 1.83 **<.0001**	6.14 (46, 49)	14.38 ± 2.60 **<.0001**	8.88 ± 2.67 **0.0024**	14.89 ± 6.31 **0.0346**
Taraxacum officianale	7.21±2.77 **0.0101**	2.60 (30, 179)	7.31±4.93 0.1429	0.53±3.73 0.8881	12.68±4.65 **0.0092**

Table 5.2. Changes in First Leaf Date (FLD) between historical (H) (1826-1878) and contemporary (C) (2009-2017) time periods for 12 commonly observed species (n > 60, except for Cercis, Tilia, and Ulmus, n>3 per time period, per zone), as indicated by t-test. Difference is given in days ± one standard error. Statistically significant ($p < 0.05$) values are highlighted in orange. Zone 4 was omitted because most of these species did not occur frequently in that zone. Dashed lines indicate zones without adequate representation, n<3 per time period.

USDA Hardiness	All Zones		Zone 5	Zone 6	Zone 7
Species	Difference/ p-value	T statistic/ *N=(C, H)*	Difference/ p-value	Difference/ p-value	Difference/ p-value
Acer rubrum	14.12 ± 3.48 **<.0001**	4.05 (349, 19)	10.55 ± 6.80 0.1241	13.75 ± 4.12 **0.0011**	---
Acer saccharum	13.56 ± 2.41 **<.0001**	5.62 (236, 29)	13.30 ± 3.14 **<.0001**	11.53 ± 4.03 **0.0054**	15.55 ± 6.71 **0.0237**
Cornus florida	22.33 ± 5.01 **<.0001**	4.45 (127, 14)	13.26 ± 6.93 0.0765	30.69 ± 9.51 **0.0020**	16.16 ± 5.09 **0.0025**
Cercis canadensis	26.75±7.16 **0.0013**	3.74 (19, 4)	---	22.25±7.69 **.0340**	---
Fraxinus americana	14.08 ± 6.15 **0.0239**	2.29 (102, 8)	---	31.88 ± 13.41 **0.0262**	16.52 ± 8.02 **0.0438**
Lindera benzoin	27.11 ± 9.45 **0.0046**	2.87 (183, 14)	18.90 ± 16.62 0.2642	25.66 ± 14.29 **0.0388**	31.11 ± 18.09 **0.0445**
Liriodendron tulipifera	25.95 ± 4.20 **<.0001**	6.18 (128, 14)	---	21.19 ± 4.29 **<.0001**	24.40 ± 6.69 **0.0004**
Prunus serotina	13.75 ± 4.41 **0.0021**	3.12 (168, 10)	20.17 ± 3.97 **<.0001**	---	11.35 ± 6.77 0.0944
Querus alba	28.08 ± 12.34 **0.0263**	2.28 (81, 18)	22.71 ± 3.97 **<.0001**	10.31 ± 3.33 **0.0074**	23.71 ± 5.60 **0.0001**
Syringia vulgaris	13.57 ± 3.88 **0.0007**	3.50 (71, 28)	25.08 ± 5.22 **<.0001**	20.00 ± 4.54 **0.0001**	10.76 ± 8.12 0.2214
Tilia americana	13.21 ± 2.76 **<.0001**	4.79 (15, 20)	18.24 ± 4.27 **0.0007**	11.70 ± 3.80 **0.0068**	6.36 ± 6.62 0.3690
Ulmus americana	18.34 ± 3.95 **<.0001**	4.65 (20, 21)	22.80 ± 10.74 **0.0389**	---	15.27 ± 6.37 **0.0269**

Table 5.3. Results of ANCOVA describing the relationship between explanatory variables and First Flower Date (FFD) and First Leaf Date (FLD) (as measured by Day of Year, DOY) across all species. Hardiness Zone – zone 4, 5, 6, or 7, as designated by US Department of Agriculture; Mean Spring Temperature – mean temperature in January-April (°C); Seasonality – early spring (DOY 60-120), late spring (DOY 121-152), and summer (DOY 153-196); Life Form – forb, shrub/small tree, or tree.

First Flower Date

Fixed Effects	**DF**	**DF Den**	**F Ratio**	**P-value**
Mean Spring Temperature (continuous)	1	2647	261.3	**< 0.001**
Seasonality (categorical)	2	2645	1232.0	**< 0.001**
Life Form (categorical)	2	2645	5.0	**0.007**
Life Form*Seasonality (categorical)	4	2644	34.9	**< 0.001**
Random Effects	**Var Comp**	**%**	**SE**	**Wald P-value**
Hardiness Zone (random)	37.7	12.9	31.7	0.23

First Leaf Date

Fixed Effects	**DF**	**DF Den**	**F Ratio**	**P-value**
Mean Spring Temperature (continuous)	1	1956	236.9	**< 0.001**
Seasonality (categorical)	1	1955	128.7	**< 0.001**
Life Form (categorical)	1	1955	2.9	0.09
Life Form*Seasonality (categorical)	1	1955	11.2	**0.001**
Random Effects	**Var Comp**	**%**	**SE**	**Wald P-value**
Hardiness Zone (random)	71.0	24.3	60.0	0.23

Table 5.4. Changes in First Leaf Date (FLD) and First Flower Date (FFD) between historical (1802-1861) and contemporary (2009-2017) time periods for species according to Seasonality and Life Form. Significant p-values are highlighted in orange.

Season (FLD)	Life Form	Difference	t Ratio	DF	Prob > t
Early Spring	Shrub/Tree	15.86 ± 2.15	7.38	699	**<.0001**
	Tree	17.74 ± 1.47	12.10	1095	**<.0001**
Late Spring	Shrub/Tree	16.72 ± 7.13	2.35	42	**0.0238**
	Tree	15.56 ± 2.11	7.37	124	**<.0001**
Season (FFD)	Life Form	Difference	t Ratio	DF	Prob > t
Early Spring	Forb	5.46 ± 1.53	3.58	198	**0.0004**
	Shrub/Tree	12.52 ±3.34	3.75	199	**0.0002**
	Tree	10.04 ± 1.52	6.59	732	**<.0001**
Late Spring	Forb	-0.75 ± 1.37	-0.55	478	0.5845
	Shrub/Tree	12.88 ±1.58	8.16	402	**<.0001**
	Tree	21.69 ± 3.05	7.12	350	**<.0001**
Summer	Forb	9.61 ± 4.29	2.24	94	**0.0274**
	Shrub/Tree	3.75 ± 4.87	0.77	61	0.4441
	Tree	-5.00 ± 6.72	-0.74	129	0.4576

Table 5.5. Changes in First Flower Date (FFD) for commonly observed species (>20 observations in each of urban and rural areas with the exception of Caltha palustris N=15 in urban locations) according to Urban-Rural Classification. Difference represents change in FFD between historical (1826-1878) and contemporary (2009-2017) time periods. Significant p-values are highlighted in orange.

Classification	Rural				Urban			
Species	Difference	t	df	p	Difference	t	df	p
Acer rubrum	12.00±3.18	3.77	172	**0.0002**	17.24±2.67	6.45	228	**<.0001**
Acer saccharum	11.23±1.93	5.83	69	**<.0001**	9.03±4.72	1.92	61	**0.0300**
Asclepias syriaca	4.96±4.37	1.14	32	0.2645	16.82±12.41	1.35	41	0.1829
Caltha palustris	15.83±4.87	3.25	20	**0.0040**	-1.42±4.41	0.32	13	0.7532
Cornus florida	3.26±4.46	0.73	42	0.4683	21.80±2.90	7.53	85	**<.0001**
Erythronium americanum	2.15±2.12	1.01	53	0.3149	13.40±3.38	3.97	41	**0.0003**
Lindera benzoin	2.88±4.06	0.71	48	0.4814	16.30±6.05	2.70	100	**0.0083**
Liriodendron tulipifera	14.15±4.63	3.05	30	**0.0047**	32.29±6.66	4.85	102	**<.0001**
Maianthemum canadense	-1.09±4.24	-0.26	20	0.7999	6.23±4.62	1.35	50	0.1838
Populus tremuloides	7.18±6.49	1.11	21	0.2812	3.83±6.78	0.57	19	0.5783
Prunus serotina	2.33±5.92	0.39	33	0.6960	2.38±5.32	0.45	90	0.6530
Querus alba	1.70±6.34	0.27	31	0.7900	22.50±5.09	4.42	28	**0.0001**
Syringa vulgaris	8.53±3.63	2.36	37	**0.0241**	11.99±2.63	4.56	54	**<.0001**
Taraxacum officinale	4.78±9.89	0.48	55	0.6306	6.80±2.50	2.72	150	**0.0073**
Ulmus americana	20.89±9.85	2.12	23	**0.0449**	14.96±4.95	3.02	40	**0.0044**

Table 5.6. Changes in First Leaf Date (FLD) for commonly observed species – Urban-Rural Summary Table – Species with sample sizes over 10 in both categories were included. (>20 observations in each of urban and rural areas with the exception of Fraxinus americana and Ulmus americana, N=14, 11 respectively) according to Urban-Rural Classification. Difference represents change in FFD between historical (1826-1878) and contemporary (2009-2017) time periods. Significant p-values are highlighted in orange.

	Rural				Urban			
Species	Difference	t	df	p	Difference	t	df	p
Acer rubrum	17.76±5.61	3.16	160	**0.0019**	13.47±4.39	3.07	204	**0.0024**
Acer saccharum	13.41±3.80	3.53	158	**0.0005**	15.84±3.38	4.68	102	**<.0001**
Cornus florida	21.00±9.22	2.28	49	**0.0271**	23.29±6.01	3.87	87	**0.0002**
Fraxinus americana	9.58±2.93	3.26	12	**0.0068**	8.50±7.57	1.12	94	0.2648
Liriodendron tulipifera	21.53±6.58	3.27	24	**0.0032**	27.34±4.95	5.53	112	**<.0001**
Querus alba	19.32±3.55	5.45	42	**<.0001**	23.12±3.72	6.22	52	**<.0001**
Syringa vulgaris	9.49±7.26	1.31	40	0.1986	20.01±4.23	4.73	53	**<.0001**
Tilia americana	15.56±4.31	3.61	15	**0.0026**	12.28±4.59	2.68	17	**0.0159**
Ulmus americana	16.13±8.81	1.83	9	0.1002	18.93±4.44	4.26	28	**0.0002**

Table 5.7. Results of ANCOVA describing the relationship between explanatory variables Mean Spring Temperature, Seasonality and Pollination Syndrome and First Flower Date (FFD) (as measured by Day of Year, DOY) across all tree species. Mean Spring Temperature – mean temperature in January-April (°C); Seasonality – early spring (DOY 60-120), late spring (DOY 121-152), Pollination syndrome – wind or insect.

Fixed Effects	DF	DF Error	F Ratio	P-value
Mean Spring Temperature (continuous)	1	979	183.9	**< 0.0001**
Seasonality (categorical)	2	979	530.6	**< 0.0001**
Pollination Syndrome (categorical)	1	979	31.4	**<0.0001**
Model	**4**	**979**	309.6	**<0.0001**

Table 5.8. Changes in First Flower Date (FLD) between historical (1802-1861) and contemporary (2009-2017) time periods for tree species according to season and pollination syndrome by t-test. Wind pollinated tree species N=262, Insect pollinated tree species N=690. Significant p-values are highlighted in orange.

Flowering Season	Pollination Syndrome	Difference	t Ratio	DF	Prob > t
Early Spring	Wind	10.06 ± 2.93	3.24	109	**<.0009**
	Insect	14.81 ± 1.78	8.28	556	**<.0001**
Late Spring	Wind	15.95 ± 4.44	2.35	149	**<.0001**
	Insect	27.50 ± 5.03	5.46	134	**<.0001**

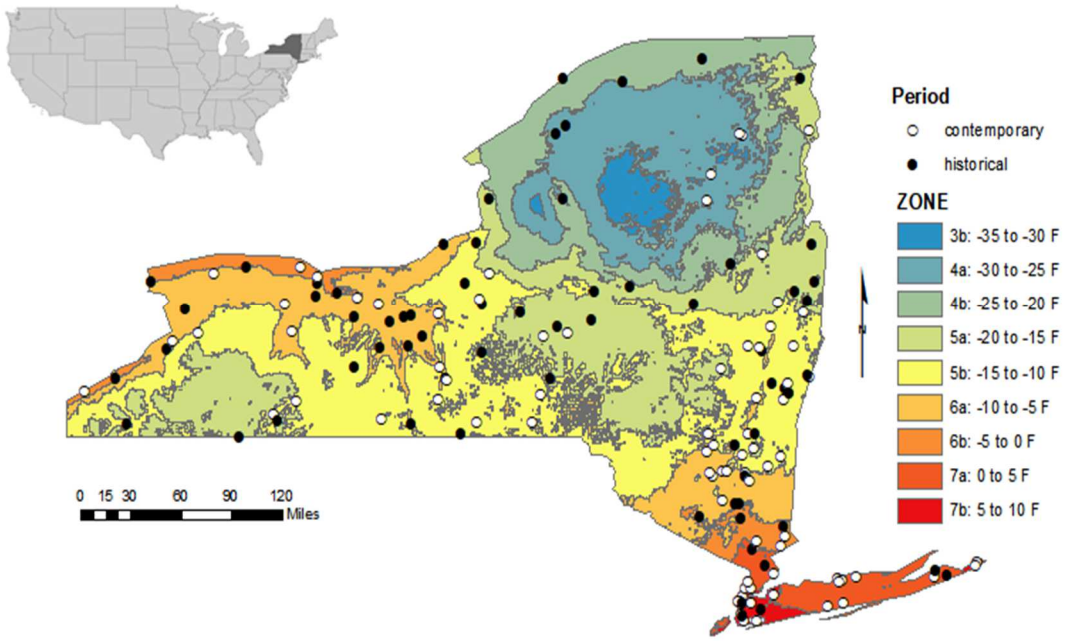


Figure 5.1. Geographic projection map of historic and modern phenology monitoring sites across New York, USA, with US Department of Agriculture Hardiness Zones indicated. Historic locations (N=66) are indicated by black circles and contemporary locations (N=88) by white circles. Historic time period spanned years *1802-1861, and contemporary time period spanned years 2009 -2017.*

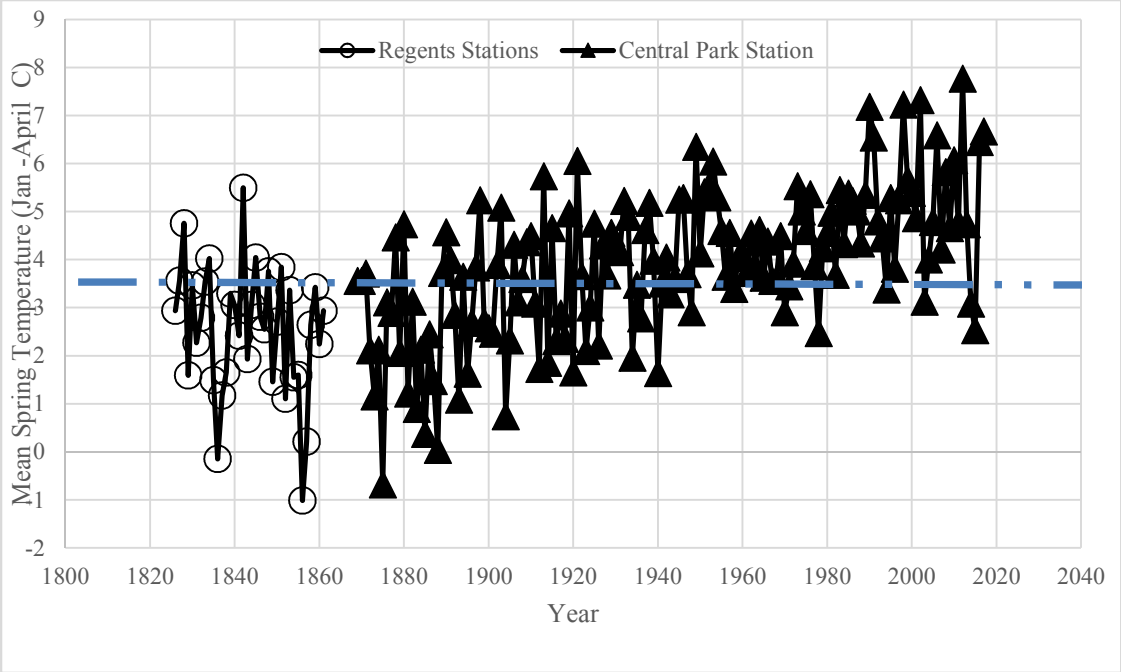
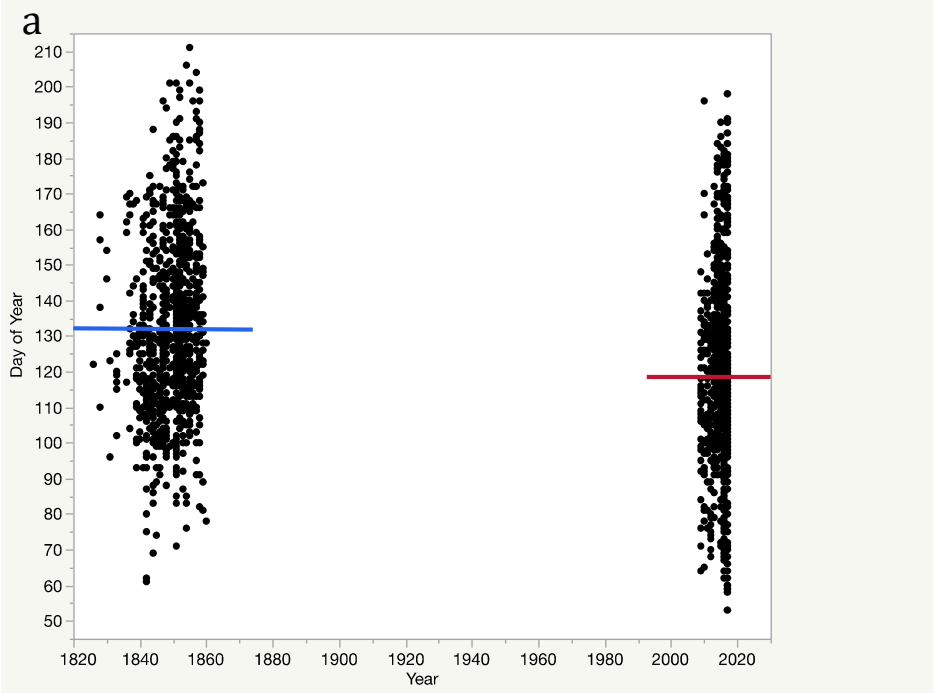


Figure 5.2. Mean Spring Temperatures (January-April) at four sites in New York City 1826-2017. Open circles represent years 1826-1861, compiled from Regents data (average of historic stations at Fort Columbus, Erasmus Hall, and Union Hall). Triangles represent years 1869-2017 from Central Park, downloaded from NOAA (NOWData). The blue dash-dot line shows the Mean Spring Temperature for the entire data set, 1826-2017 (3.7°C).



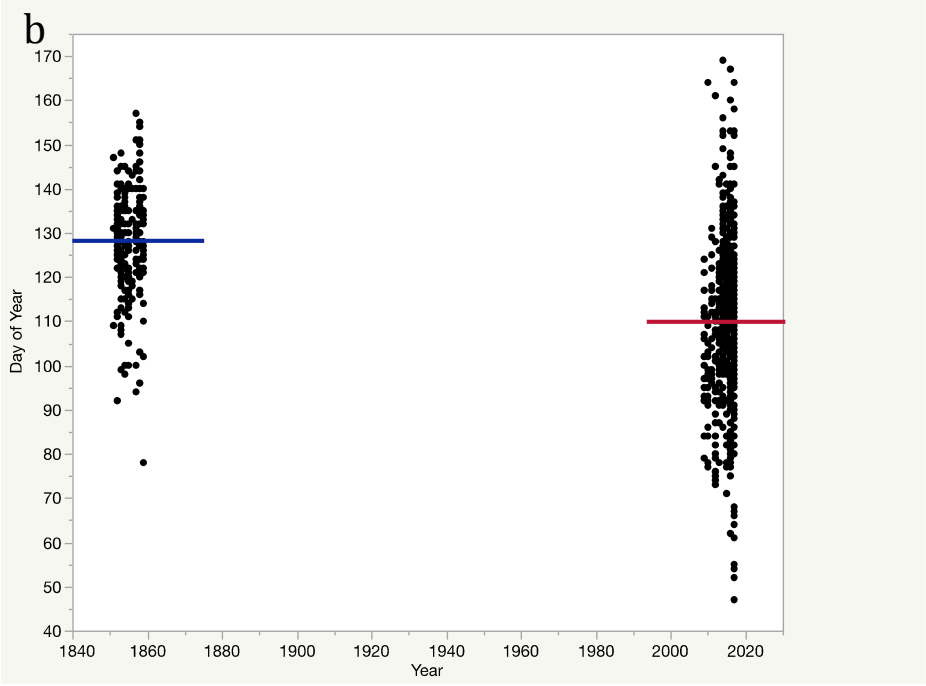


Figure 5.3. Changes in (a) First Flower Date (FFD) and (b) First Leaf Date (FLD) across all species over time. Each point represents an observation of the phenophase for one species in one location in one year. FFD and FLD occurred on average 11.1 and 18.8 days earlier in the contemporary time period, respectively. (FFD: $t = 11.2$, $n = 2659$, $p < 0.001$; FLD: $t = 17.9$, $n = 2071$, $p < 0.001$). Blue line drawn at historic mean, red line drawn at contemporary mean to highlight change between Time Periods.

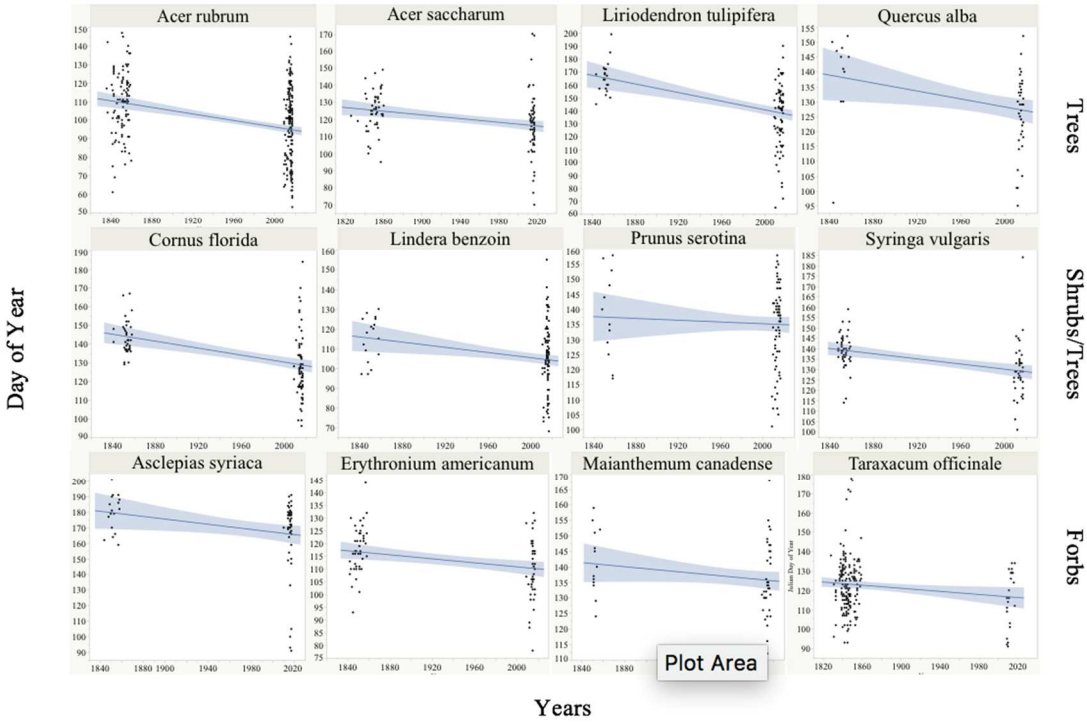


Figure 5.4. First flower date (FFD) of individual species grouped by Life Form (trees, shrubs/small trees, and forbs). All species had sample sizes greater than 60, and had representation in at least two Hardiness Zones. Each point represents one observation of each species in one location in one year. Analysis was by t-test (results in text). Best-fit trend lines are shown to highlight differences between time periods; shaded areas represent standard errors for trend lines.

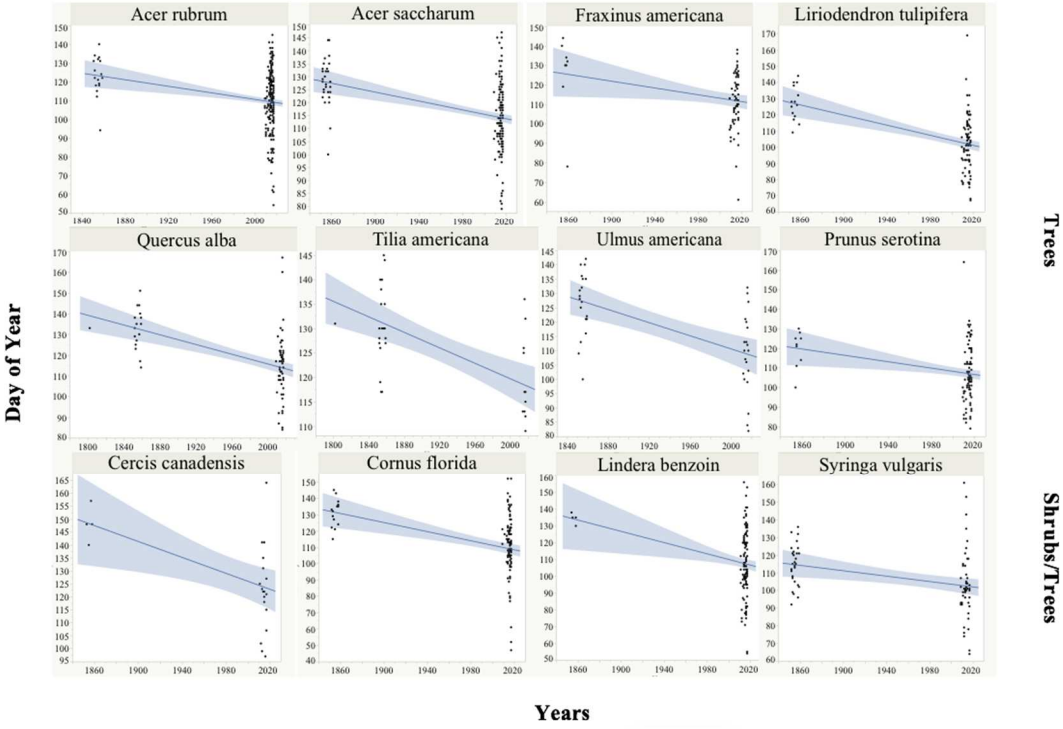


Figure 5.5 First Leaf Date (FLD) of individual species grouped by Life Form (trees and shrubs/small trees). All species had sample sizes greater than 60 (with the exception of Cercis n=23, Tilia=35, and Ulmus n=41), and had representation in at least two Hardiness Zones (with the exception of Cercis). Each point represents one observation of each species in one location in one year. Analysis was by t-test (results in text). Best-fit trend lines are shown to highlight differences between time periods; shaded areas represent standard errors for trend lines.

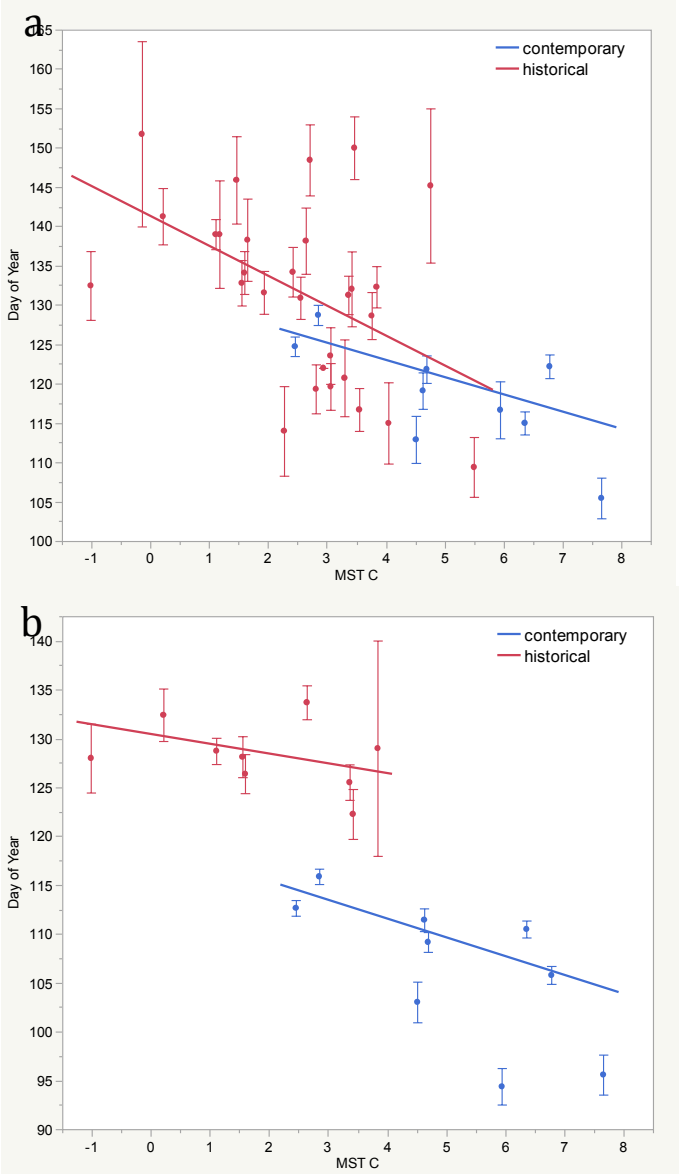


Figure 5.6. Relationships between Mean Spring Temperature (MST) and (a) First Flowering Date (FFD) and (b) First Leafing Date (FLD) averaged across all species. Each point represents the mean (a) FFD or (b) FLD for all species observed in each year; error bars represent one standard error. Red represents historical data, blue contemporary data. Best fit lines are shown; shaded areas represent standard errors for trend lines. Regression results for FFD: $R^2 = 0.07$, slope = -3.2 days/°C, $p < 0.001$; for FLD: $R^2 = 0.13$, slope = -3.0 days/°C, $p < 0.001$.

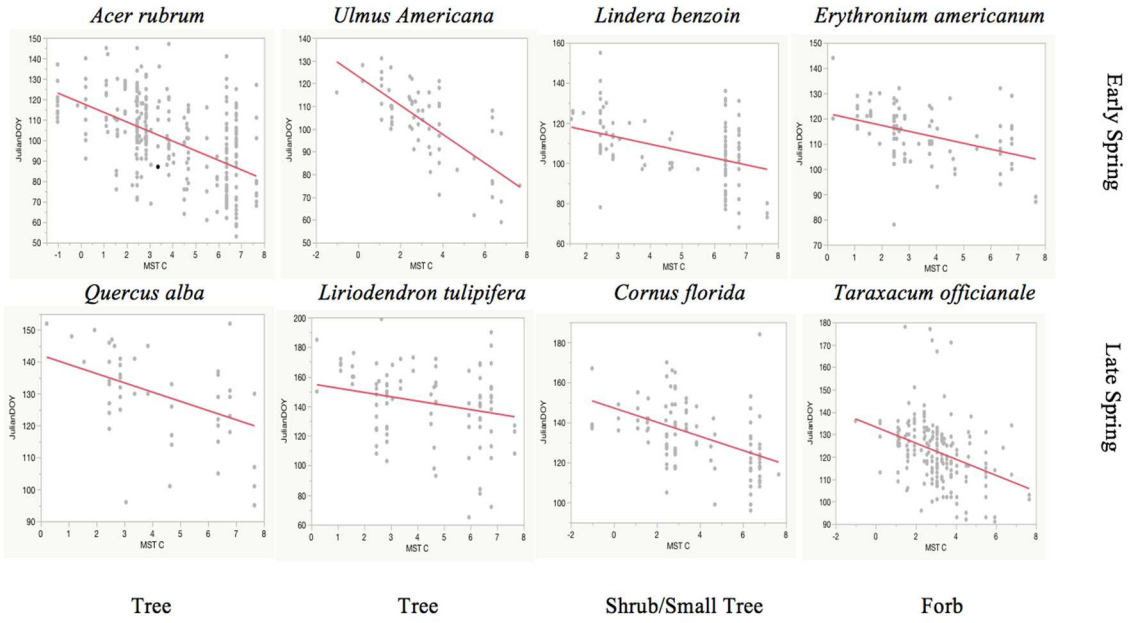
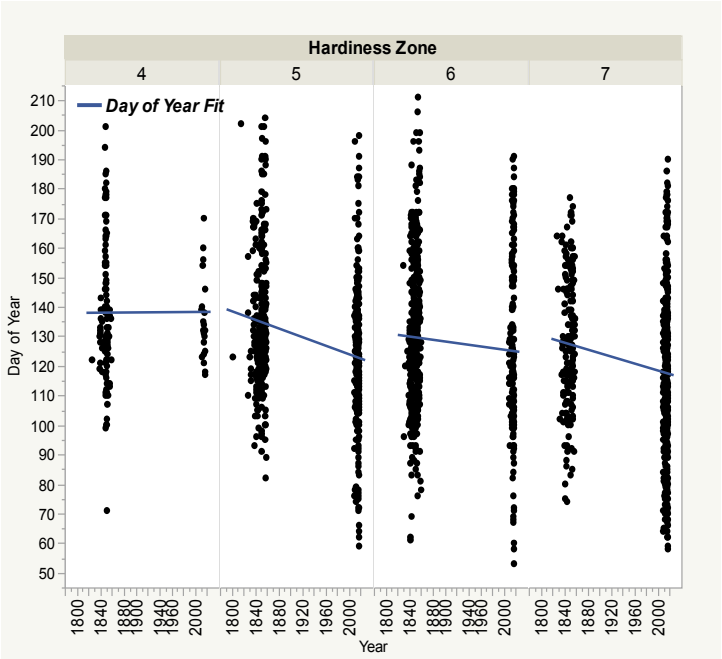


Figure 5.7. Relationships between Mean Spring Temperature (MST) and First Flowering Date (FFD) for eight of the most commonly observed species in our data set, grouped by Seasonality and Life Form, as indicated by linear regression. Observations are all from the historic time period to avoid change of weather stations from historic to contemporary period. Each point represents one observation of FFD at one location in one year. Regression results provided in text; best fit lines shown here. *Acer rubrum* $R^2 = 0.30$, slope = -4.7 days/°C, $p < 0.001$; *Cornus florida*: $R^2 = 0.23$, slope = -3.5 days/°C, $p < 0.001$; *Erythronium americanum*: $R^2 = 0.02$, slope = -2.4 days/°C, $p < 0.001$; *Lindera benzoin*: $R^2 = 0.18$, slope = -3.4 days/°C, $p < 0.001$; *Liriodendron tulipifera*: $R^2 = 0.06$, slope = -2.9 days/°C, $p = 0.003$; *Quercus alba*: $R^2 = 0.19$, slope = -2.9 days/°C, $p < 0.001$; *Taraxacum officianale*: $R^2 = 0.15$, slope = -3.6 days/°C, $p < 0.001$; *Ulmus americana*: $R^2 = 0.51$, slope = -6.3 days/°C, $p < 0.001$).

a



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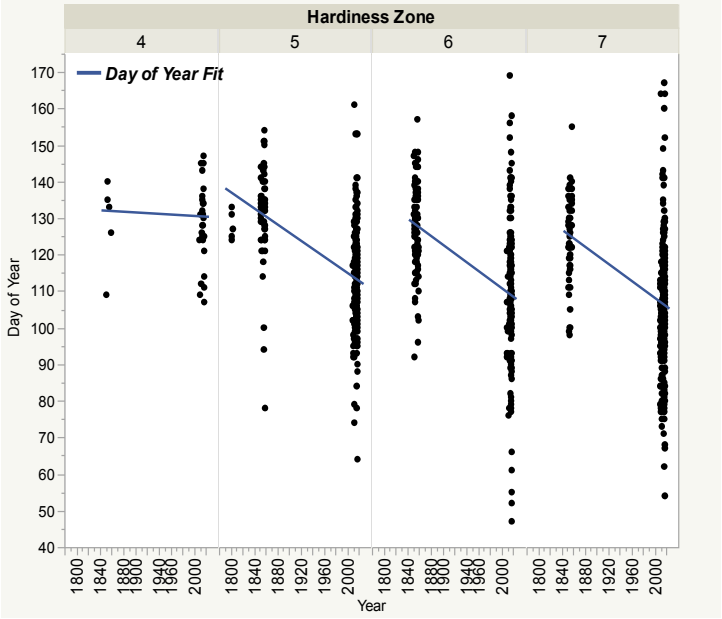


Figure 5.8. Changes in (a) First Flower Date (FFD) and (b) First Leaf Date (FLD) over time with species categorized by Hardiness Zone. *FFD and FLD for s*pecies in zones 5, 6, and 7 occurred significantly earlier in the contemporary time period, as indicated by t-test ($p < 0.001$, except for FFD in zone 5, where $p = 0.010$). FFD and FLD for species in zone 4 did not show a significant change between the historical and contemporary time periods. Each point represents an observation of (a) FFD or (b) FLD of one species in one location in one year. Best-fit trend lines are shown to highlight changes in phenology between time periods; shaded areas represent standard errors for trend lines.

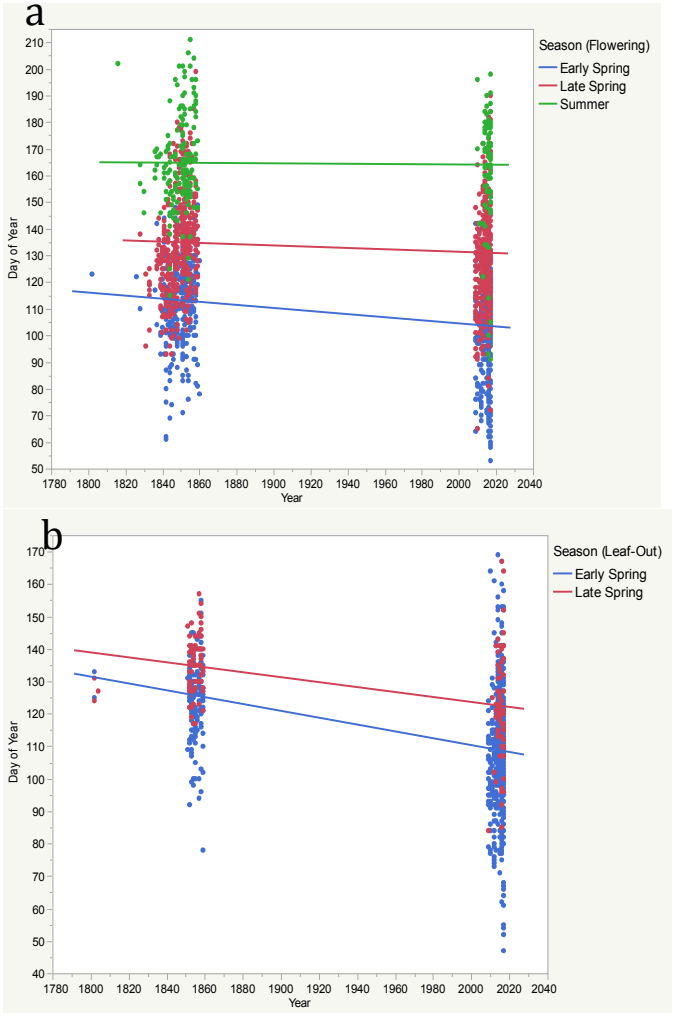


Figure 5.9. Changes in (a) First Flower Date (FFD) and (b) First Leaf Date (FLD) for species grouped by Seasonality of phenology (early spring, late spring, or summer). Blue lines represent early spring, red lines represent late spring, and green line represents summer. Best-fit trend lines are shown to highlight differences between time periods; shaded areas represent standard errors for trend lines. For species with early- and late-spring phenologies, FFD and FLD occurred earlier in the contemporary time period. For early-spring species FFD occurred 9.7 days earlier ($t = 8.80$, $p < 0.001$), FLD occurred 17.0 days earlier ($t=13.80$, $p < 0.001$). For late-spring species FFD occurred 4.3 days earlier ($t = 4.38$, $p < 0.001$), and FLD occurred 12.8 days earlier ($t = 6.17$, $p < 0.001$). For summer species FFD did not change significantly between time periods ($t=0.47$ $p = 0.64$).

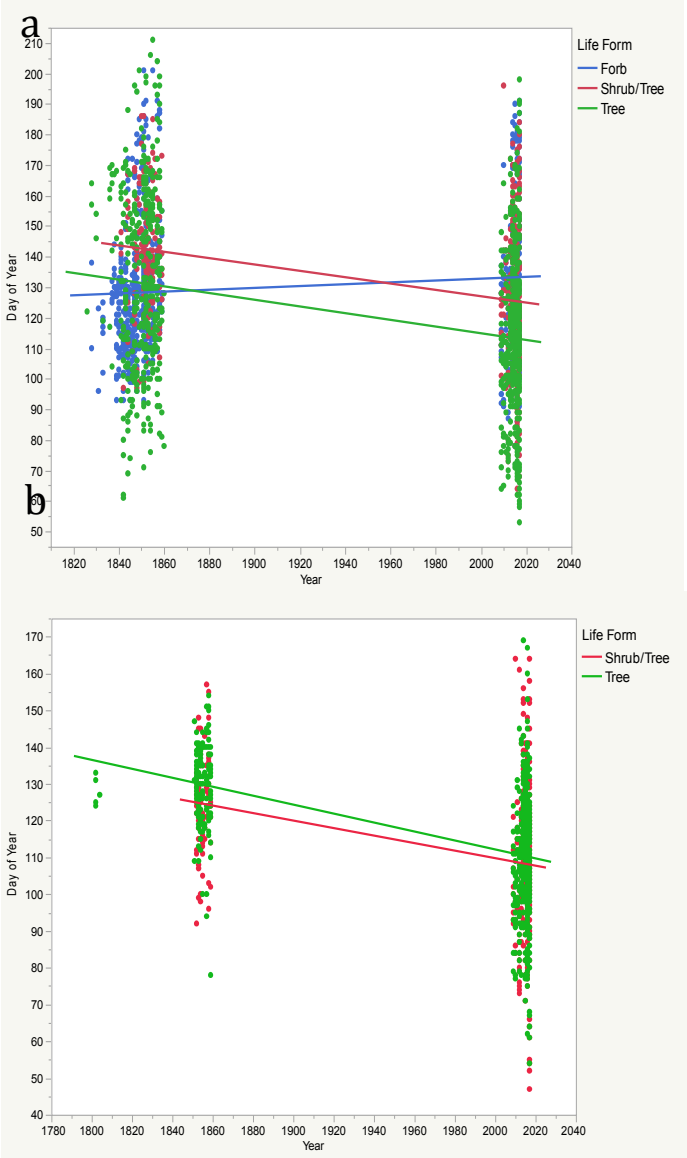


Figure 5.10. Changes in (a) First Flower Date (FFD) and (b) First Leaf Date (FLD) with species grouped by Life Form (forb, shrub/small tree, or tree). Red lines represent shrubs/small trees, green line represents trees and blue line represents forbs. FFD and FLD occurred significantly earlier in the contemporary time period for shrubs/small trees and trees. For shrubs/small trees: FFD occurred 16.9 days earlier ($t = 8.92$, $p < 0.001$), and FLD occurred 16.4 days earlier ($t = 7.64$, $p < 0.001$). For trees: FFD occurred 18.1 days earlier ($t = 11.22$, $p < 0.001$), and FLD occurred 19.9 days earlier ($t = 16.97$, $p < 0.001$). For forbs, FFD occurred 4.4 days later in the contemporary period compared to the historic period ($t = -2.71$, $p = 0.007$). Best-fit trend lines are shown to highlight differences between time periods; shaded areas represent standard errors for trend lines.

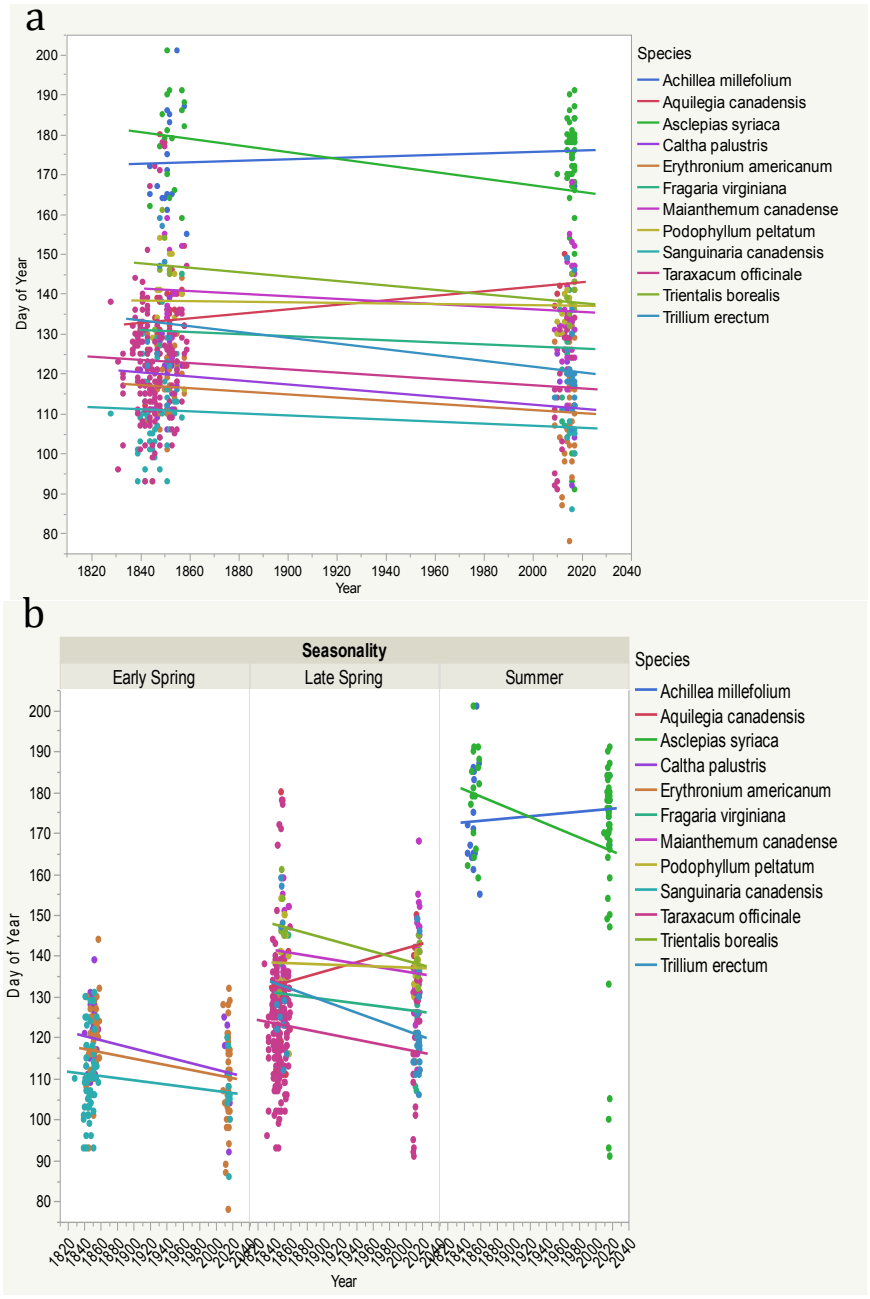


Figure 5.11. Changes in First Flowering Date (FFD) (a) all forb species included in our analysis, and (b) forbs by season in both time periods. Two late season forbs with higher distribution in the historic set appear to be affecting the overall historic mean for forbs. The other ten forbs all have earlier flowering dates. Best-fit trend lines are shown to highlight differences between time periods; shaded areas represent standard errors for trend lines.

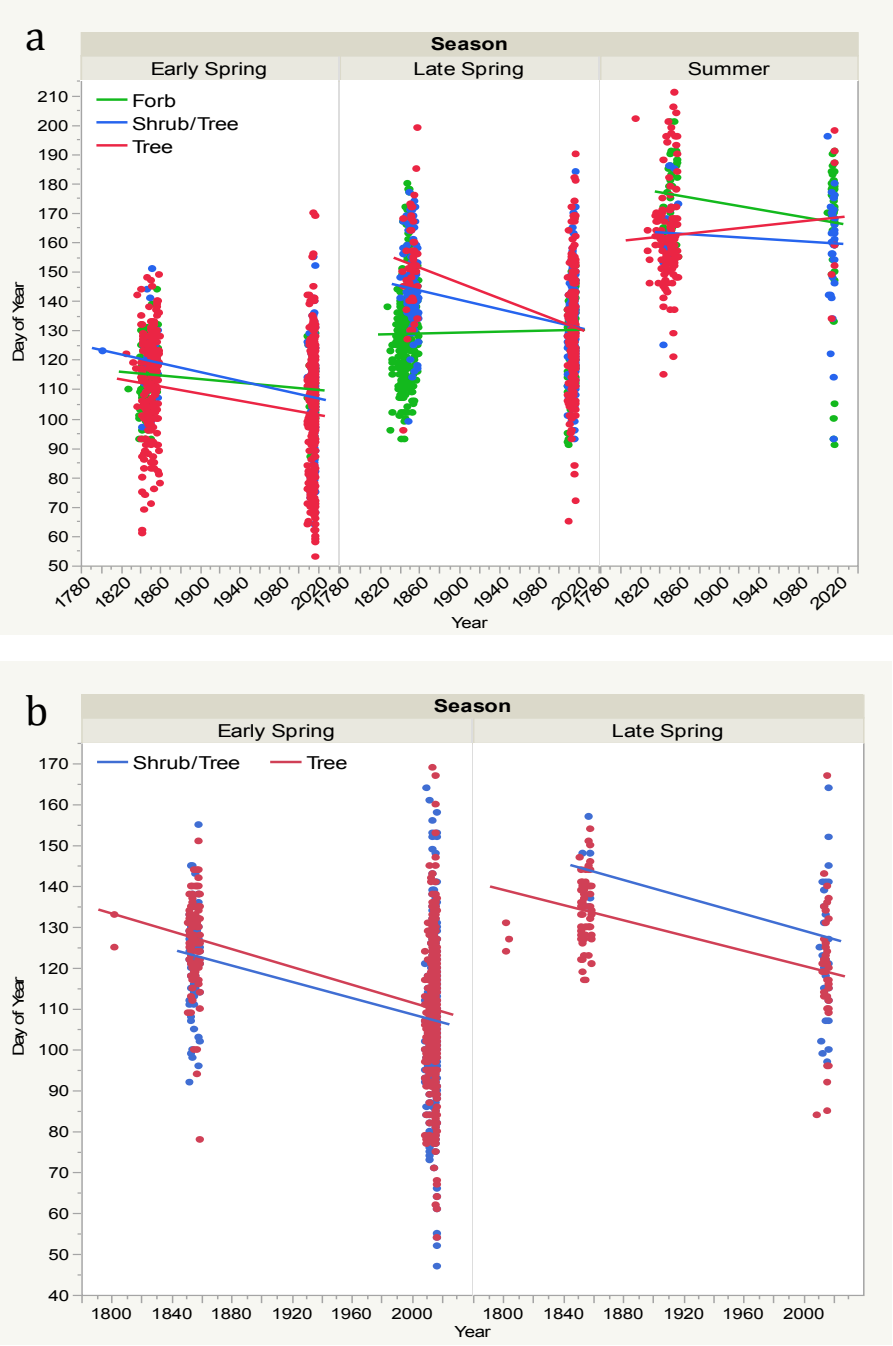
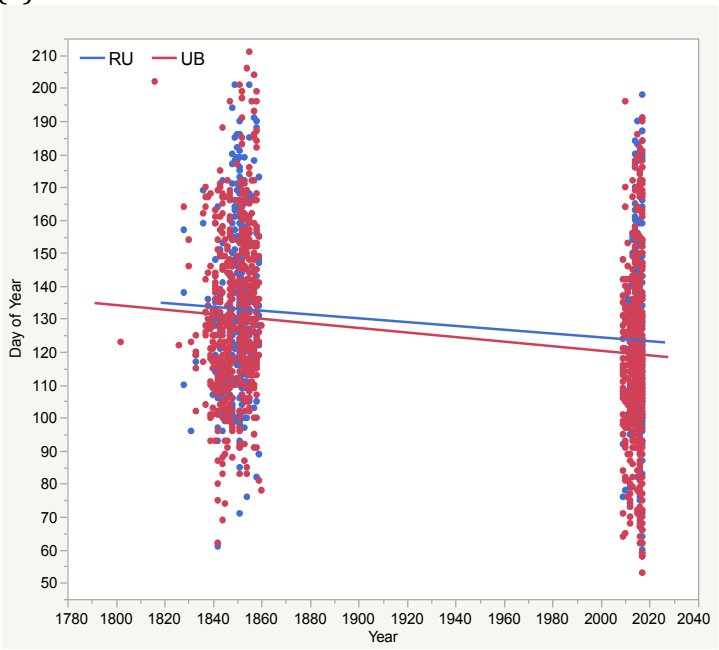


Figure 5.12. Changes in (a) First Flower Date (FFD) and (b) First Leaf Date between historical (1802-1861) and contemporary (2009-2017) time periods, with species grouped by Seasonality (panels) and Life Form (trees in red, shrubs/small trees in blue, and forbs in green). Each point represents one observation of FFD for one species at one location in one year. Best-fit trend lines are shown to highlight differences between time periods; shaded areas represent standard errors for trend lines.

(a)



(b)

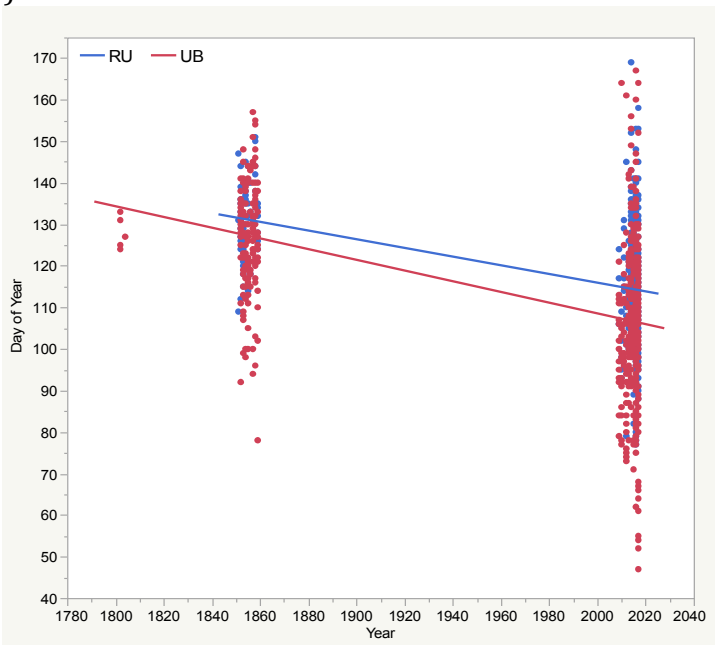


Figure 5.13. Changes in First Flower Date (FFD) (a) and First Leaf Date (FLD) (b) over time with observations grouped by Urban-Rural Classification. Each point represents an observation of FFD or FLD for one species in one location in one year; observations in urban locations are in red, rural locations in blue. Best-fit trend lines are shown to highlight differences between time periods; shaded areas represent standard errors for trend lines.

Chapter 6.

Conclusion

The volume of citizen and community science efforts being launched in recent years is unparalleled and many have enormous potential to make an ecological difference. For these efforts to be effective and sustainable, however, closer attention must be paid to key components that can promote resilience. Through the lens of public participation in plant-pollinator conservation, we have, with rigorous social-ecological inquiry, offered three foundational assessment areas that can provide scientific support to this nascent field: accuracy, ecological significance and the potential to scale. We have also demonstrated the value of scaled networks powered by ecologically significant, accurate citizen science data collection efforts.

In Chapter 2, we explored a common concern about citizen science – that a lack of foundational knowledge, or familiarity with following scientific protocols could lead to inaccurate data collection (Hunter et al. 2013). Specifically, our study demonstrated that citizen scientists collected accurate plant phenology data at an overall rate of 91% and a transitional rate of 70%, which validated national protocols for volunteer collected plant phenology data. Our evaluation of the different phenophases, functional groups and species allowed us to make recommendations to the USA-National Phenology Network (USA-NPN), and likely other plant phenology networks) on the categories that yielded the highest accuracy rates. These most accurate phenophases were “unfolded leaves” and “ripe fruit,” and the functional group “shrubs” was more accurate than trees. Moreover, we determined that variations in volunteers’ abilities to correctly identify phenophase

status were in part a function of conditions specific to certain species and functional groups. For example, errors increased for certain species that had small or inconspicuous flowers, or when phenophases on canopy trees were too difficult to see effectively even with binoculars. Our results (both general and specific) were used to refine subsequent iterations of the national protocols used by USA-NPN and add particular features to the phenophase descriptions that could better address the conditions specific to certain phenophases, species or functional groups. We also identified future areas of research that were then undertaken by USA-NPN to better explore variability in volunteer assessments. We focused this study on plants as a first step in determining this particular protocol's amenability to community science. We have since explored the next steps of adding pollinator species to track phenological synchronization (temporal connectivity), which we will address in future research.

In Chapter 3, we explored a common concern that restoration efforts implemented by the public may not have adequate ecological value. Using the frame of assessing small-scale pollinator patch plantings, we addressed key ecological variables to determine how small-scale patches attracted pollinators and explored which of these variables might be best to prioritize for restoration efforts suited to public initiatives. This study demonstrated that in small-scale plant restoration sites, plant diversity and resource (nectar) availability can significantly affect the abundance and diversity of pollinating insects. Specifically, the treatments which contained high-resource (nectar-rich) plant species increased pollinator abundance and diversity the most. Plant diversity increased pollinator diversity and abundance only in the absence of high-resource plants. Pollination facilitation was observed in high resource treatments but varied among

species. Competition for pollinators was observed in high diversity treatments but did not affect seed set for high-resource plants in any of the treatments. Together, these results suggest that managers or landowners who are restoring patches of native plants as habitat for pollinators should prioritize including species with high nectar production, and secondarily, a diverse mix of species if space and resources allow. Our study is first we are aware of that isolates the effects of diversity (from functional diversity and surrounding landscape factors) by controlling for patch size. In addition, the patch assessment protocols we used to monitor pollinators were designed to be adoptable by observers with limited training. They have since been tested with volunteer and non-scientist observers (Battle, unpublished data) and adopted by multiple programs such as the Gateway National Recreation Area Environmental Education Program and Vassar College's Farm and Ecological Preserve.

In Chapter 4, an exploratory case study of the New York Phenology Project, we explored an emergent approach to public participation in regional community science initiatives (and networks.) We demonstrated that local organizations have the opportunity to utilize existing data aggregation platforms to activate regional collaborative alliances to achieve what is often challenging for large–scale contributory projects. Activating regional collaborative alliances as a mechanism to accelerate citizen science is an emerging approach to public participation in science research and has not been adequately studied. Our study is the first we are aware of that describes first-hand the experience of launching a regional network and outlines a model that could be used as a guide for any catalyst entity (an individual or organization launching an effort) or a national citizen science platform endeavoring to utilize a large-scale data aggregation

platform as the initial activation mechanism for a regional network. Our unique position as both a catalyst entity and a researcher examining public participation in conservation afforded us a novel opportunity to evaluate organizational attributes that can promote network node success. Drawing on our direct experience and interviews with our network partners we developed a description of key categories related to network node success, and a linked assessment tool that could be used to evaluate network node capacity and project outcomes.

Our preliminary findings suggest that certain organizational and project attributes such as type of institutional commitment and participant-focused project management (community-building efforts, attention to project materials and hands-on training) appear linked to project success. The assessment tool we developed could be used to further test these preliminary findings in a more formal quantitative and qualitative exploration. In Appendix C.3, we describe a design that uses metrics available through the open source USA-NPN platform that could address many of the elements described in this descriptive case-study. We plan to use this design in future research endeavors.

In Chapter 5, our exploration of an exceptional long-term, community-level phenology dataset that spans New York State, USA (1802-2017), found interesting and significant patterns of phenological change over time. The dataset provides statewide phenology and temperature data that extend further back in time than any previously known dataset for the region, extending to years prior to or at the beginning of recent human-caused global warming (Stocker et al. 2013). We found that most species are flowering and leafing earlier in recent years (2009-2017) than they did in the early 19th century (1802-1861). Plants are flowering 11 days earlier and leafing 18.8 days earlier—

with some species flowering up to 27 days earlier and leafing up to 31 days earlier over that time period. We determined that most of this change was driven by warming mean spring temperatures (MST) over that time; mean spring temperatures warmed by 1.0°C statewide (2.5°C in New York City) on average between the historical and contemporary periods. Seasonality, Life Form, and the interaction between Seasonality and Life Form explained variation in phenology among species. The large number of geographically distinct sites in this dataset permitted novel investigation into differential changes in phenology between urban and rural areas. We found larger changes occurring in urban habitats, likely driven by warmer temperatures in those urban areas. In addition, our study is the first we know of that has documented a difference in phenological responsiveness due to pollination syndrome with ground-collected historical data over a large geographic region. Insect-pollinated tree species showed a significantly greater phenological advancement than wind-pollinated ones in the contemporary time period.

This study contributed novel findings to a fairly limited body of knowledge on how climate change and urbanization have affected the phenology of certain plant species in the Northeast. Moreover, our specific findings related to life form, seasonality, pollination syndrome and urban acceleration may help researchers determine which species, or groups of species, to include in their examinations of the ecological and evolutionary impacts of non-synchronous phenological changes among organisms. In addition, this exploration has provided significant evidence that this unusual dataset is an invaluable new resource for exploring biological response to climate change. Our analysis has brought the efforts of a historical network into a modern context and has

illustrated how organized long-term monitoring efforts can be valuable for ecological discovery.

Extending the work

This dissertation has contributed original empirical research to multiple fields of study within the broad realms of ecology and plant-pollinator conservation. However, during the process of carrying out the research, I made links with many organizations and stakeholders whose interests and goals aligned with mine. Thus, the contributions of this dissertation expand beyond the empirical research highlighted in each chapter. Examples include:

- Launching *The New York Phenology Project (NYPP)*, a growing collaboration (including nature centers, academic research & education institutions, national parks, public education institutions, land trusts and more) that is amplifying the ecological power of its communities by providing training and data collection sites for the individuals, students, and teachers who visit and staff who work there. Each organization has launched an independent phenology monitoring initiative that meets the particular mission of their organization while collecting high quality data that is aggregated by the National Phenology Network and available to researchers across the world.

- Assembling numerous local communities through talks and workshops focused on how individuals and communities can plan their gardens and landscaping projects to encourage pollinator health.

- Conducting trainings and workshops with K-12 teachers (in both rural and urban settings) to explore methods of bringing phenology monitoring and pollinator habitat restoration into the classroom.

- Participating in and presenting at various summits on ways to reimagine public space and engage the public in the intersections between our social-cultural lives and our ecological citizenship (including, New York City's *Eco Flora Project*, an invitation only gathering of 30 policy makers, city-planners, historians, scientists and land managers, as well as *Arts, Data and Ecology* on behalf of the US Forest Service New York City Urban Field Station which included botanists, visual artists and scientists from the region.

- Helping coordinate novel ecological interventions – such as an effort to control the invasive Hemlock Wooly Adelgid by partnering with the New York State/Cornell biocontrol initiative and the USA-National Phenology Network to get HWA listed as a national phenology species so that we could train the NYPP monitoring sites to gather the data needed for the biocontrol release calendar.

- Catalyzing and/or supporting other types of community science monitoring projects such as the Growing a Wild NYC program, which brings underserved public schools to a National Park (Gateway Recreational Area) in partnership with the National Wildlife Federation to restore habitat destroyed by Super Storm Sandy by planting pollinator habitat in part with seeds grown in their own classrooms.

- Providing directional advice and ongoing guidance to the producers of *The Crowd and the Cloud* (recently featured on PBS) in order to highlight and celebrate real world examples of citizen and community science (NYPP phenology work was featured in Episode 4.).

All of the example initiatives above share a focus on collaboration, on managing dialogue with diverse stakeholders, on practicing a deeper level of engagement to promote a wider diversity of perspective and opinion—core practices of the emergent field of translational ecology.

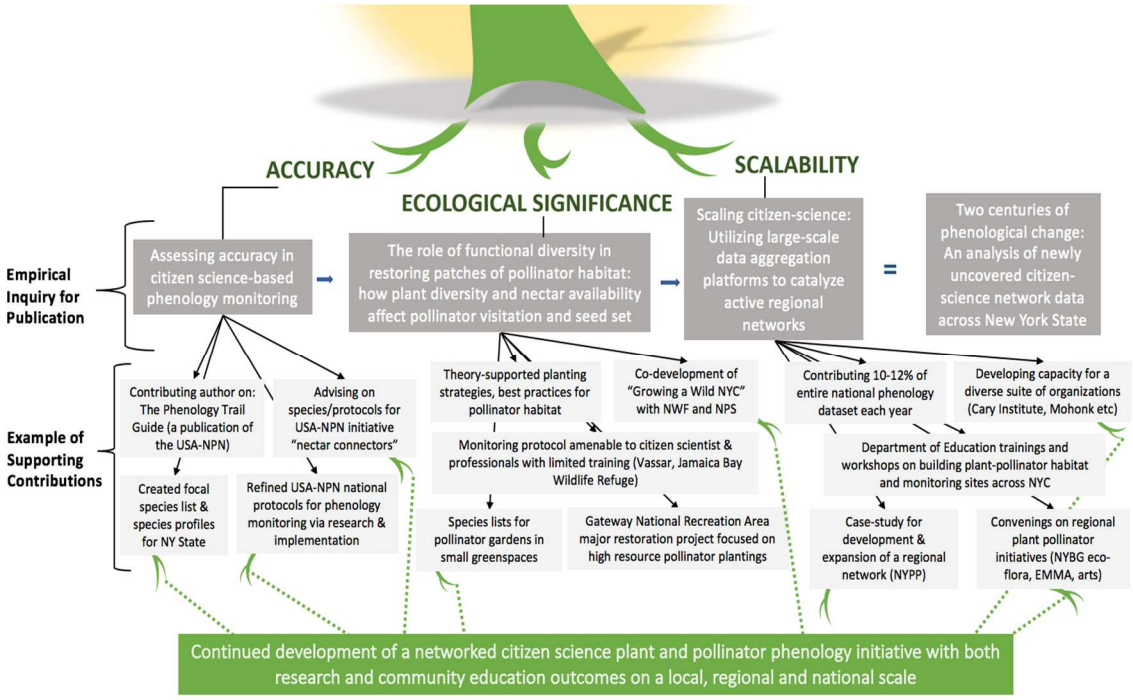


Figure 6.1. Examples of dissertation contributions that support networked monitoring and restoration initiatives.

The power of translational ecology

Translational ecology is moving from an aspiring field to a robust applied practice (see special issue of *Frontiers of Ecology and the Environment, Dec. 2017*). The term "translational ecology" was coined by William Schlesinger, who wrote in an editorial for *Science* magazine *"Just as physicians use 'translational medicine' to connect the patient to new basic research, 'translational ecology' should connect end-users of environmental science to the field research carried out by scientists who study the basis of environmental problems."* (Schlesinger 2010).

Translational ecology encourages six core practices to support those committed to this cross-disciplinary approach: collaboration, engagement, commitment, communication, process and decision-framing (Enquist et al. 2017). These are vital,

practical tools to launch, support and scale public participation. Failure to fully utilize these tools could create misunderstanding, confusion or resentment. It is important to realize that the primary focus is not to drive specific actionable science or even to create greater ecological efficiency. The primary goal of translational ecology is to develop relationship between diverse stakeholders who share a common interest (whether or not they even know it) in service of ecological inquiry and stewardship. Translational ecology is a movement to meet the unique challenges of our time. Issues around global climate change are becoming more contentious; questions surrounding local, national and global environmental sustainability are growing more complicated. As a result, diverse groups of stakeholders are seeking greater engagement and influence. Opinions differ around how to prioritize and address both problems and solutions as well protocols on how we frame practical decision-making. Land managers, policy and research experts, community activists, consumer advocates, citizens and politicians are all weighing in on environmental matters once solely the concern of ecologists. So how do ecologists remain effective in this crowded discussion? How do ecologists help lead informed and helpful dialogue? How do we assist groups with very different agendas to find alignment around vital issues of conservation and ecological sustainability? As translational ecologists, how do we bring vital information to any given ecological issue, without preempting the energy and passion of others we need to help us meet those challenges?

Metrics are still emerging that will define translational ecology's success in the long term. What we do know now is that the fundamental drive behind this movement is the same drive that is powering the proliferation of novel institutional alliances, regional collaborations, innovative pilot programs, coordinated interventions, public-private

partnerships, cross-disciplinary research and network formation in many different fields. Innovations derived from healthy and vital networks are becoming increasingly utilized across disciplines. Traditional divides, which have long existed between sectors such as business, medicine, science and education, are giving way to interdisciplinary initiatives that promote new paradigms (Bradshaw & Beckoff, 2001, McBride et al. 2011). In all these sectors (and many others), group learning, knowledge networks, and network leadership are becoming more essential to exploring questions and deriving innovative, relevant answers. These social tools and processes are consistent with, and absolutely essential to, the work being done within the burgeoning field of translational ecology. Translational ecology looks to drive the creation of social capital through social relationship. (Enquist et al. 2017). Many of us will have to become "boundary spanners", individuals who are comfortable crossing between disciplines, perspectives, even ideologies to "foster the co-production of ecological knowledge" (Safford et al. 2017). The argument is not that a choice needs to be made between translational ecology and other scientific approaches, but rather that, as F. Stuart Chapin notes, "we need to provide space, respect and rigorous training for those who decide to make translational ecology a component of their science." (Chapin 2017).

Closing thoughts

In the process of developing this body of work, we had the opportunity to experience firsthand what it means to work in the field of translational ecology. As we explored public participation in restoration and monitoring we zeroed in on the factors associated with what catalyzes networks of community scientists. While there is considerable research supporting the value of citizen science initiatives (Sullivan et al. 2009, Delaney et al. 2008, Paulos et al. 2008), our explorations of network scalability illustrated that there is less focus on the details of actual network creation and maintenance. From our explorations into data accuracy and ecological significance we learned that there are specific ways that this field needs scientific support to continue to flourish. From our direct experience launching a community-science effort, we learned that organizations that want to engage in citizen science monitoring and conservation techniques must have the attributes and resources to sustain the effort and connect it to the larger community or region. We learned, from the many meetings and assemblies we hosted or participated in, that robust stakeholder engagement and relationship—no small feat to accomplish—is essential to launching community science projects and bringing ecological insight (and actionable science) to the communities most in need of them. We learned through our own successes and failures that a highly visible and compelling emphasis on the ecological relevance of network activity keeps people coming back to the collective work.

And finally, through the practice of engaging communities in ecological monitoring, we have gained a fundamental insight into how to address some of our most perplexing ecological challenges through public participation. The insight is simply this:

make the challenges relevant and accessible to people where they are – in the context of where they live, what they already care about and how they are capable of contributing. The application of ecological theory of natural systems to managed landscapes (e.g., temporal connectivity, facilitation, patch dynamics in planted systems) can actually become personal and relevant to urban and residential gardeners; vegetation lists and future planting strategies to maximize pollination services and plant reproductive success in managed landscapes can matter to homeowners; creating long-term plant- pollinator phenology data sets can offer teachers a whole new way to meet STEM requirements. We even saw that a phenology trail could offer spiritual practitioners (Zen monks) a way to extend their mindfulness practice.

Opportunities to implement valuable conservation techniques and monitoring efforts while simultaneously deepening civic engagement for communities are worth the effort. As stakeholders find common purpose, they begin to organize themselves around common principles, identifying key components of problem and solution that matter to all of them. Successful community science collaborations have the potential to become self-sustaining networks of activity. They can promote the essence of social capital (goodwill, mutuality, trust, cooperation, etc.), form around common cause with one another while, at the same time, pursuing their own compelling initiatives. When we offer the right experiments inside accessible opportunities with clear goals and standardized procedures, we can inspire a whole new array of individuals who can actively, efficiently assist ecologists and conservationists in our most vital work. 

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Chapter 1: Introduction

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Chapter 5. Two centuries of phenological change: An analysis of newly uncovered citizen-science network data across New York State

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Appendix A: Chapter 3 Supplemental Information

Appendix A.1 Detailed Plant Species Information (reproductive strategy, conservation status)

HR (high nectar/high pollen reward):
Liatris spicata (self incompatible, rare/endangered in wild)
Monarda fistulosa (self compatible but reproductive success increased by outcrossing, common in wild)
Pycnanthemum munitum (self compatible, rare/endangered in wild)

Intermediate Resource species to add diversity (some nectar and or pollen reward)
Veronicastrum virginiana (not often on "high resource" lists, considered med)
Phlox maculata (showy, self-incompatible rare/endangered in wild)
Rudbeckia hirta (common, easy to grow, showy, but not consistently high reward)

LR species (low nectar and/or pollen reward):
Filipendula rubra (self incompatible, no nectar, some pollen, visually showy, but rare in wild)
Spirea tomentosa (showy, decent pollen, very low nectar)
Coreopsis rosea (self incompatible, rare/endangered in wild)

Appendix A.2 - Outline of theoretical concepts, hypotheses and testable response variables.

Theoretical Concept	Hypotheses	Response Variables	Taxanomic Focus
Patch dynamics: (patch composition affects patch quality, which in turn affects pollinator visitation rate and pollinator diversity. Pollinato choose patches based on best opportunities) to forage for resources	Pollinator diversity and visitation rate (abundance per 25 min) will vary significantly across patches with varied species composition. Visitation rate will be highest in in patches with highest resource levels	# visitors & taxonomic diversity of visitors	Pollinators
Diversity: High floral diversity is correlated to high pollinator diversity	High diversity treatment patches will support higher diversity of floral visitors than low diversity treatment patches. Higher floral diversity will reduce abundance of floral visitors (due to decreased abundance of high resource flowers	# visitors & diversity of visitors	Pollinators
"The Magnet Effect" Patches with high resource levels (nectar/pollen) will attract pollinators at a higher rate than patches with low resource levels (less attractive	Patches that contain "magnet" or HR species will receive higher visitation rate (abundance) by a greater number of pollinator species (diversity) compared to patches without HR species	# visitors & diversity of visitors,	Pollinators and Plants
Facilitation: The presence of certain flowering species increases pollinator visits to other species,	There will be more visits to low resource species when in patch with high resource species, Proximity to HR species will increase seed set of LR species within patches	Visitation rate to LR species when in patch with HR species vs. not; seed set of focal LR species	Pollinators and Plants
Competition: Competition for pollinators can limit reproductive success for plants through reduced visitation and/or increased interspecific pollen transfer (stigma clogging)	HR species will receive fewer visits in HD patches and will have lower seed s than HR species in LD patches LR species will not experience reduced seed set in presence of HR species	Visitation rat to HR species Seed set of focal HR species Visitation rate & seed set of focal LR species	Plants

Appendix B: Chapter 4 Supplemental Information

Appendix B.1 - Categories of inquiry to evaluate network node success

Institutional Commitment: Is it necessary? How does the strategic direction by a host institution influence the performance of a successful citizen science network? We will closely examine the assumption that when phenology observation is approached as a means to directly support the institution's science, management, or outreach goals (as opposed to simply an ephemeral activity), the likelihood is it will be sustained over time. Do we actually see this pattern in practice? Can a network launch itself without the active sponsorship of a host institution? What does the institution need to provide to its staff and participants to enable a network to develop itself? How engaged must senior leadership of these institutions be in order to incubate a network? How are costs weighed against benefits? How do the institutions value these networks, if at all? Some organizations identify a locally relevant, tractable research or management question embedded in their phenology monitoring effort. Does this approach correlate to program success? Does the regional focus of the questions and associated monitoring regime benefit the national dataset or compromise impact at the national level while accelerating impact at the regional/local level?

Strategic Goals & Governance: developing specific/clear/purposeful strategic goals to encourage agile leadership and effective management models. Some programs have a clear and specific question they are addressing and some have as their goal basic broad-scale monitoring, or perhaps early detection. Does it make a difference to have specific goals with targeted deliverables (i.e a certain amount of data collected per season, a commitment to utilizing the data imminently for publication or management)? The engine of goodwill that powers citizen science networks perhaps must be fueled by purpose, clarity of mission and achievable strategic goals. What is necessary, beyond the general desire to help? Community science calls for a measure of dedication and a devotion of consistent service. How is that created? How is it nurtured and developed?

Governance is a key to the open management of network efforts (Conrad & Hilchey 2011) What governance models best serve effectiveness and scale? There are traditionally deployed tools to successfully manage citizen science networks (Fiorino 1990)—how are they changing? At a more tactical level, what are the leadership profiles for those who are instrumental to a network's success? What leadership attributes are most crucial (practical orientation vs. intuitive, detailed vs. conceptual, transactional vs. relational, scientific vs. social?) to promoting volunteer enthusiasm and dedication? While all networks possess unique and distinctive success factors, what commonalities of project management can be derived from close analysis? Small failures of leadership can be catastrophic to a network's resilience while subtle attentions to the care and consideration of the network (and its volunteers) can generate energy, passion and dedication. Nuanced leadership and a deep knowledge of the way networks flourish is critical to the ongoing success of a given network. What are the traits of a network leader? How does leadership move from an authority model (command and control) to an

influence model? One of the consequences of true network leadership may, in fact, be a kind of invisibility (Leskovec 2008) where the most active network nodes "blend in" alongside larger and smaller ones. Can that be modeled or replicated in any way?

V**olunteer Training: learning what models are most valuable**. What are the benefits of training? Does arming citizens with a more thorough and detailed understanding of their tasks (through study materials and training modules) yield better, more accurate data? What is the amount of time needed and is the expense and effort worth it? What kind of training is most valuable—online learning, hands-on learning, hybrid learning? Higher education is examining this question at its very core—but how much blended learning is necessary to give citizen scientists the tools and discernment they will need to collect data, make observations or pose pertinent and penetrating questions?

Communication Tools: Reviewing models and quality. The communication and engagement tools that a network deploys to maintain interest, engagement and focus are key (Bingham 2006). Volunteer motivation and retention appears to be a critical success factor: is it too easily overlooked? Why does one hub with the resources, the facilities and the expertise to foster and promote strong volunteer engagement utterly fail, while another lacking these obvious assets somehow generate enormous activity and data collection? Clear and relevant communication is often cited as essential to harnessing the power of interdisciplinary scientific initiatives (McBride et al. 2011, Prysby & Super 2007). How is that true for citizen science networks which can have a powerful interdisciplinary component? What must communication emphasize to keep hubs vibrant and links proliferating? What is the frequency of meetings, reminders, emails and general information blasts that stimulate the most productive engagement? What enables a hub to spawn self-developed sub hubs who, in turn, take full responsibility for sustaining their own engagement?

Instructional materials: Empowering and guiding effectively. What kind of materials are necessary to engage volunteers? Do they need printed materials? Do picture guides made a substantial difference in increasing observer confidence level in phenology monitoring? How often do observers create materials on their own? Do documents or presentations that review, summarize and graph the data collected over a season give observers a clearer picture of their own impact?

Technology: determining useable, relevant technology. Technology is the emerging and vital driver of this new and powerful alliance between the public and scientific professionals. Using technological innovations, citizen scientists have more opportunities to scale data collection around important scientific and ecological issues. Phenology is enjoying a wide range of big data technology advancements (Morisette 2009) but the hands-on work of observation and assessment also remains invaluable. The data capture of that assessment is now in the hands of innovative apps and simple algorithms on hand held devices. While smart phones, ipads, hand held-devices of all kinds often allow citizens to make clear observations and contribute direct, reliable data, is giving people tools enough? Some of these tools may or may not be deployed effectively, especially if

the participants are not comfortable with the technology or haven't been offered training to effectively utilize the technology. How do managers of conservation programs think critically about current technology adoption and how to experiment with (and exploit) new technologies as they emerge? How vital are these technologies to the growing phenology movement? What are the barriers to their increased use? Is access to technology a key success factor? Do technological glitches create major setbacks for projects and programs?

Community-building: the role and value of communities in science research. Similar to the above sections of training and communication, but different in intention, is a focus on community- building. Creating and managing a group to increase the benefits associated with group observing (more observations distributed over shorter time frames) and meet data requirements, has a different intention (and therefore a different approach), than creating and managing a group with community building at the forefront. Many studies have demonstrated social benefits for participants in citizen science and community-based monitoring programs (Schwartz 2006, Sultana & Abeyasekera 2008, Whitelaw 2003). Community science presupposes that learning is social and is best accomplished through collaborative engagement with multiple stakeholders. Attention paid to stimulating community and belonging may increase dedication, commitment and longevity. Some organizations and projects prioritize this, while others focus on focused trainings. Do these events make a difference? How many and what type of community building events give volunteers a sense of being part of an observer community?

Appendix B.2 - **Draft Survey and Interview**

1) ***Baseline Institutional Characteristics:***

-Operational Budget:
- Physical Size/location
-Staff Size (How many full time? How many part time/seasonal staff?)
- Landscape context (urban, suburban, exurban, rural)
-Budget for initiative (how much spent 1st year, 2nd year, 3rd year etc)
- Estimated yearly visitors
a. general public (community members)
b. schools
c. visiting teachers, researchers etc

2) ***Institutional Capacity for the Project:***

A. History of prior experience:

- Did your organization have a history with the content of this initiative (phenology, plant-pollinator monitoring/conservation)?
    - If so, describe:

- Did you organization already have a history of managing a volunteer network or have a "friends of" type of volunteer organization associated with your institution?
    - If so describe: a list serv, a volunteer management system etc.

- Did you as an individual have a prior interest in the content of this program (phenology, pollinators)?
    - If so please describe how you got started:

- Were you in communication with the other nodes in the network before your involvement with this project?

- Were you in communication with more than 10 schools/community organizations prior to this project?

- Is your organization widely known for hosting community events
    - If so describe: (lectures, trainings, bioblitzes, etc.)

B. Institutional commitment/Governance:

- Does your board/President/Executive Director know of this effort?
    - If so, what is their chief attraction to it? If not, why not?
- Have any job descriptions been created or changed to include activities to support this project?
    - If so, describe the new position or altered job description

- Is there targeted funding allocated to this project?

    - If so, how much and for how long?

- Has your organization sought funding or used this project as a method of seeking funding?
    - If so, who were the funders and how did you/will you use this project to attract funding?
- Does your institution give special designations to volunteers who participate in this project (free membership, special parking passes etc.)
    - If so, please describe

C. Strategic Goals:

- Do you have specific targets related to this project?
    - number of volunteers you want to recruit in a given time frame
    - volume of data you want to generate
    - education related numbers (# of teachers trained, # students experience project)
- Do you have a focused scientific question (beyond the mission of NYPP to track plant-pollinator synchronization and urbanization effects on plants/pollinators)?
    - If so, describe:
- Do you use or intend to utilize this project to advance the mission of your organization?
    - If so, describe
- Do you have strategic "incentives" that you hope to meet or have been met by this project (STEM learning, attracting potential donor, etc)

- Does your organization value the research or education impact of this project more or both equally?
    - If unequal describe proportionally

D**.** Participant focused training/communication:

- Do you communicate regularly with volunteers?
    - # emails
    - # phone calls
    - # face to face
- Do you hold group in person trainings?
    - If so, how many?
- Do you hold virtual trainings?
    - If so, how many?
- Do you use specific Community Building practices (potlucks, meet ups, social networks like Facebook:
    - If so, describe:
- Do you designate specific tasks or specific volunteers for specific tasks in your project?
    - If so, please describe

E. Resources (technology, materials)

- Do you create Instructional Materials?
    - If so describe:
- Do you create informational materials (newsletters, brochures)
    - If so describe:
- Do your volunteers submit or create resources?
    - If so describe:

- Do you provide a common resource location for staff and volunteer submitted resources (i.e. drop box, google docs)?

- Do you use Technology such as data collection apps (NPN app, other apps like iNaturalist?
    - If so describe:

3) *Social Network Analysis:*

A. Centrality and tie strength:

- Have you ever contacted another node in the NYPP network?
    - If so, who? How many times?
- Do you share observers/assets/tools/resources/information with any other node in the NYPP network? How many?
- Do you look at other organizations websites within NYPP (including USA-NPN)?
    - If so who? How many times?
- Do you ever contact USA-NPN directly?
    - If so, how often?

- Is there a person or organization that you consider the "go to" resource for questions regarding project management and protocols?
    - If so, who?

B. Diffusion: Related to your involvement with NYPP (and the associated content and activities):

- Have you engaged with other institutions or community organizations (outside of NYPP network?)
    - If so, please list and describe:

- Have you engaged with formal school groups or informal students groups related to your involvement with NYPP?
    - If so, please list and describe:

- Have you experienced any new nodes or sub-nodes forming without central oversight as a result of your project?

- If so, please list and describe

- Have you seen any demonstrations of new activities or ideas forming as a result of your project
  - If so, please list and describe

D. Role of Catalyst entity

- Was this person/organization vital to your project implementation?
  - If so, in what way?
- If this person/organization left the system would your activities still continue?
  - Why or why not?
- If this person left the system would NYPP no longer be able to function?
  - Why or why not?

4) *Outputs:* (some of this they can describe and we will correlate to numbers in open source database)

Totals: (Engaged Participants in Project):

-(how many staff, community volunteers, interns/college students)
-Teachers and Classrooms (how many students/schools?)
-Community/Public (How many access information on trail/interpretive materials/via newsletters?)
-Demographic information on participants
- How many people come to your trainings?
- How many people register in Natures Notebook?
- How many people submit data?
- How many people come to your events?
- How many observers do you consider "core"?
- What has been your retention rate?

1) Interview Questions:

a. How did your organization decide to get involved with phenology monitoring and join NYPP?
b. Do you feel that you project has been successful and impactful?
c. What are the factors that you feel have contributed to your success?
d. What are the factors that have made your experience challenging?
e. Do you think that your program will operate long term?
f. What will dictate whether it can or cannot be sustained?
g. What are some ways that NYPP can help make your program more successful?
h. What are some ways that USA-NPN can help make your program more successful?
i. Is there anything else you would like to tell us?

Appendix B.3 - Key network components and metrics for analysis

Key network components and predictor variables for analysis

- Institutional Commitment (categorical – scaled high-low)
- Strategic Goals (categorical – yes-no)
- Hands on Project Management (categorical –scaled –high-low)
- Volunteer Training (categorical and continuous)
- Process and Materials (categorical – scaled, but may be quantified)
- Technology (categorical)
- Community building (categorical – scaled, but maybe quantified by # of events)
  * some of these variables will be explored qualitatively, but will have aspects that are measurable (i.e. how many volunteer trainings are run during the year)
- Population density, (continuous)
- Regional demographics (categorical and continuous)
- Time established (continuous)

Key metrics and response variables for analysis

- Number of observers (continuous)
- Data volume (continuous)
- Data accuracy (outlier rate) (continuous)
- Data consistency (rate of N before Y) (continuous)
- Observer Retention rate (continuous)

Appendix C: Chapter 5 Supplemental Information

Appendix C.1 Data Download and Collation Methods

Download: All modern data was downloaded from USA-NPN's Observation Data Portal

1. USA-NPN Main Website: https://www.usanpn.org/
2. Under Data tab, click Observational Data - https://www.usanpn.org/data/observational
3. Go to Phenology Observation Portal
4. Individual Phenometrics selected – considers sites as independent, captures individual species as opposed to average species (which is called Site Phenometrics)
5. Date Range: data between 2007-2017
6. Region Selector: NY State
7. Phenophases: Flowers and Leaves
8. Partner Groups: Initially New York Phenology Project partners, then combined all data collected in New York State, including Individual Observers not affiliated with organized programs
9. Output fields: Observed By Person ID, Partner Group, Site Name, Phenophase Category, Multiple FirstY (not specifically utilized during this process)
10. Download: 29037 data points

Once downloaded, data was reduced based on several parameters

Species specific edit

- Any species that was not present in both the historic and modern data set was removed
- If less than two observations were present for a species in either time period the species was removed
- Kingdom Animalia was not included
- Any agricultural phenophases or categories were removed
- Modern data set had 20 categories for phenophases removed that were not 'Breaking leaf bud' or 'Open flower'
- 193 contemporary species were removed because there was no historic data comparison or there was only one observation
- 716 historic species were removed because there was no modern comparison or their identification was not to species level
- Outliers were removed based on the other dates of their Hardiness Zone
- Total reduction to 4278 contemporary observations
- Total reduction to 1453 historic observations
- Data collation continued during analysis, and more observations were removed (species that had less than three years of data, or drastically uneven distributions across time period or hardiness zones.
- Final dataset yielded 4730 observations across time periods.

Appendix C.2 - Historic Phenology and Weather Protocol:

Summary: In the historical dataset, one person reported observations per species per year per site. The historic protocols did not specify whether to look at the same individual plant per species each year, therefore we don't know whether the same exact individual plant was monitored year after year. This differs from the contemporary dataset in that observers are asked to tag an individual plant and monitor it from year to year. Also, multiple individuals of the same species could be monitored at the same contemporary site. The vast majority of the observations were limited to one species per location per year. However, multiple individuals of the same species could be monitored at the same contemporary site, though this occurred infrequently at a small number of locations (and only for very common species—e.g., *Acer rubrum).* The rest of the historic protocol descriptions are found below:

Period	Historic Protocol Instructions (1826-1872)	Sources/Comments
1826-1849 or 1850, Depending on when and how quickly the new instructions were adopted by the various academies	"The right hand pages are to be appropriated to observations on vegetation, and also such miscellaneous remarks as may be considered interesting; such as thunder and lightning, hail storms, tornadoes or hurricanes, destructive floods, uncommon meteors, white or hoar frost, the first appearance of barn swallows in the spring, and occasionally the depth of snow on the ground, and its disappearance, &c. The observations on the Phenomena of Vegetation are to be directed to the time when the white or red Currants blossom, when the Shadbush or Juneberry and the Dogwood trees are in their natural situation, and the Peach, Pear and Apple trees, in open fields, are in bloom; that is, when at least one-half the blossoms are fully expanded. When the flowers called aments or catkins of the White Oak, the Chestnut, the Black Birch and the Aspen begin to drop. When ripe field Strawberries first appear in any quantity. When the Wheat harvest commences. When the last killing frost occurs in the spring, observed on tender buds, young leaves, or the germs of fruit trees or other vegetables;	While the original circulars that were sent out with instructions in 1826 have not been located, all indications point to a continuity of instructions. In the sources we have found, the text at right first appears in the 1838 *Instructions from the Regents of the University, to the Several Academies Subject to their Visitation*. The same instructions subsequently appear in the 1845 *Instructions from the Regents of the University, to the Several Academies Subject to their Visitation* and are indicated to be a reprinting of the 1841 *Instructions*, those having all been sent out (two copies to each academy). Finally, in Franklin B. Hough's compilation and summary of the 1826-1850 results, published in 1855, he repeats the same instructions as being those directing the results during the 1826-1850 period.

	and the first killing frost in the fall of the year, noticed by its destroying tender plants, such as the vines of cucumbers, melons and beans."	
1850 or 1851-1872 Some observers did have the new instructions by mid-1850 and may have begun using them; others may have waited for the new year. Hough's summaries, however, only appy to observations beginning in 1851, when all would have been using the new instructions.	*A new format is described:* "In the register the first page is devoted to regular observations; the second to additional observations, to periodical or extraordinary phenomena, and to monthly recapitulations. The headings of the columns indicate clearly the use of each." There is a "broad column for Casual Phenomena" in which "periodical and extraordinary phenomena will be inscribed, with their dates and the hour of their appearance." *Basic Instructions* "The periodical phenomena of vegetation and of the animal kingdom, such as the epoch of the appearance and the fall of the leaves, of the flowering and ripening of the more generally cultivated fruits; the seed time and harvest of plants; the coming and going of migratory birds; the first cry of the frogs, the appearances of the first insects, &c.; the moment of the closing of rivers, lakes and canals by ice, and of their opening; the temperature of the springs at different periods of the year; the temperature in the sun compared to that observed in the shade; that of the surface, and that below the surface of the ground. All observations of this kind are valuable." *Invitation to request additional special instructions* "Besides the above directions for keeping an ordinary Meteorological Journal, more special instructions for the study of peculiar meteorological	In 1849 the Regents decided both to revamp their observations by the issuance of new equipment and procedures (including a selection of academies to carry these out), hiring Professor Guyot to oversee matters and combining their efforts with the Smithsonian Institution's observation system that was just being devised. This change was announced to the academies in a circular sent out in the fall of 1849, which promised instructions would be forthcoming, but they were not sent until the summer of 1850 due to delays occasioned by a fire at the printer. We have not found a copy of the instructions sent in 1850, but we do have the 1858 *Directions for Meteorological Observations, and the Registry of Periodical Phenomena*, which are described as a reprint of the original directions drawn up in 1850 by Professor Guyot with a series of additions in brackets and special pamphlets of instructions, such as on 'periodical phenomena' that it seems had only been previously available by request. It is unclear whether or not to assume that the "Registry of Periodical Phenomena" in this 1858 circular was widely available from 1850-1858. I have assumed that it was, or at least was available to those whose phenology observations from this period were summarized. This is based on the fact that Hough's 1864 compilation and summary of results from the period of 1851-1859 (despite the confusing fact that the title states the results are from 1854-1859) references the two columns for describing

	phenomena are prepared by the Smithsonian Institution, as on….Periodical phenomena of the vegetable and animal kingdoms… If any observer should feel inclined to devote himself to the study of any one of these physical problems, he may receive, on application, the special instructions relating to the point which he wishes to investigate. [These instructions now form a part of this pamphlet.]" *From the "Registry of Periodical Phenomena"* "The Smithsonian Institution, being desirous of obtaining information with regard to the periodical phenomena of animal and vegetable life in North America, respectfully invites all persons who may have it in their power, to record their observations, and to transmit them to the Institution. These should refer to the first appearance of leaves and of flowers in plants; the dates of appearance and disappearance of migratory or hybernating [sic] animals, as mammals, birds, reptiles, fishes, insects, &c.; the times of nesting birds, of moulting [sic] and littering of mammals, of utterance of characteristic cries among reptiles and insects, and anything else which may be deemed noteworthy. The Smithsonian Institute is also desirous of obtaining detailed lists of *all* the animals and plants of any locality throughout this continent. These, when practicable, should consist of the scientific names, as well as those in common use; but when the former are unknown, the latter may alone be given. It is in contemplation to use the information thus gathered, in	flowering that are described and imprinted in this register. Notably, he references it because he has chosen to collapse these two columns into one for the purpose of his summary. We have the original data and can undo this if desired. It is not clear whether Hough applied this same technique of collapsing the two flowering columns in his 1872 compiling and summary of results for the period of 1850-1871. Because of his evident desire for consistency I will assume that he did for the moment, though that may not be correct. The most recent printing of these instructions that we have is 1860, the same as in 1858. There is no indication that the protocol changed between 1860 and 1872, and in fact Hough states in his 1873 compilation and summary: "The system of making and reporting observations was not materially changed through the whole period. The attention of observers was occasionally called, by circulars, to special subjects of interest connected with the phenomena of animal and vegetable life, auroras, halos, meteors, magnetism, etc., and many interesting data were reported in addition to those prescribed by the instructions."

	deducing general laws relating to the geographical distribution of species of the animal and vegetable kingdoms of North America.... The points in the phenomena of plants, to which attention should be directed, are: -- 1. *Frondescence, or leafing.* -- When the buds first open and exhibit the green leaf. 2. *Flowering.* -- When the anther is first exhibited: -- *a.* In the most favorable location; *b.* General flowering of the species. 3. *Frutification.* -- When the pericarp splits spontaneously in dehiscent fruits, or the indehiscent fruit is fully ripe. 4. *Fall of leaf.* -- When the leaves have nearly all fallen. The dates of these various periods should be inserted in their appropriate columns. When the observations for the year are complete, they should be returned to the Institution, with the locality and observer's name inserted in the blank at the head of the sheet." *From 1964 Hough's description of his methods of summarizing the results from 1851-1859* "...In the blank circulars issued for obtaining the following data, two columns were usually provided for entering the dates of flowering of plants. One of these was designed to include the dates of first appearance of blossoms, and the other those of general flowering of the species. The former was more generally filled, and has therefore been selected for our classification; and in cases where no entry was made in the first column, that of the second has been adopted, by applying, in	

	most cases, a correction of from two to six days. Entries presenting apparent errors have generally been omitted, and in doubtful cases such disposition was made of the record as the circumstances required."	

Weather protocols:

The historic dataset included weather observations at each station (temperature and precipitation). Similar to the phenology observations, the monitoring protocols changed slightly between 1825-1849 and 1850-1878, again becoming more detailed and standardized in the latter time period overall. The slight differences in the temperature protocol (the only data we use in this analysis) between the earlier and later historic time period relate to the way the mean daily temperature was recorded. The way that modern daily mean temperature is recorded is also slightly different than either of the historic protocols (and also varies across time and type of equipment used), but the general technique for all is to average the minimum and maximum temperature of a given day. We used the monthly means that were provided in the historic summary publications of the data and subsequently combined the months of January, February, March and April to calculate Mean Spring Temperature in the historic time period and the contemporary time period. We determined this level of comparison to be coarse enough to render the slight differences in daily temperature protocols insubstantial in our comparisons of Mean Spring Temperature between the two time periods. Further fine scale analyses may need a different methodology to adequately capture protocol differences across sites in the historic time period.

Appendix C.3 - Areas for Future Research:

This study provided significant evidence that this unusual dataset is an invaluable new resource for exploring biological response to climate change. The spatial and temporal range, exceeding that of most other phenological studies in North America to date, allow for new lines of questioning and methodologies that may provide important answers to some of the ecological questions most pertinent to current global change research. The analysis described in this study only scratches the surface of what we can learn from a comparison of two networks of dedicated phenological observers separated by two centuries of time. Bringing the efforts of a historical network into a modern context explicitly illustrates how organized long-term monitoring efforts can be valuable for ecological discovery. Interest generated by the compelling narrative of a historical citizen-science effort of this magnitude can be valuable in increasing public awareness of biological response to climate change, and how the public can contribute valuable data used by researchers to answer pressing ecological questions. Here we describe some of the opportunities for future study.

Species interactions and phenological synchronization:
Both the historic dataset and the modern NYPP/USA-NPN database have animal data available. We began to explore the species cross-over in each dataset and quickly realized that this exploration was best suited for a subsequent analysis, after the baseline plant phenology data was evaluated for utility. With the foundational evidence for plant phenology changes provided by this study, and the unique spatial capabilities of this dataset, subsequent studies can explore the possible relationships between plant and animal changes over time to address important questions around phenological synchronization between trophic levels (Bartomeus et al. 2011, Wood & Kellerman 2015, Thackeray et al. 2016). For example, some of the species that show earlier flowering in our study (i.e., *Ascleipas syriaca, Lindera benzoin, Acer rubrum*) are particularly important nectar sources for pollinators. Knowing that they are experiencing such advanced phenology, particularly in urban areas, can direct future investigations on phenological synchronization.

Other Life Stages:
Trophic level interactions are usually specific to particular life stages of organisms, referred to as "phenophases." Many phenology studies, such as this one, are focused on Spring phenology and the leafing and flowering phenophases, which are usually compared to Spring temperature. Other seasons have received much less attention. Autumn phenology, for example, is vastly understudied despite key phenophase occurrence such as leaf senescence, fruit ripening, bird and insect migration and hibernation/diapause (Gallinat et al. 2015). Long-term observational datasets indicate that on average, leaf senescence is delayed by increasing temperatures (Menzel et al. 2006). An extended growing season can have many ecosystem level effects, such as allowing perennials to sequester more carbon (which in turn affects climate) (Richardson et al

2010), or giving invasive non-native plants an added advantage over native species (Fridley 2012). The historic and modern dataset both contain data related to autumn phenology such as leaf senescence, fruit ripening and bird migration, which we did not include in this analysis due to limited representation of common species across spatial range. However, comparisons for broader categories (such as bird migration or deciduous tree leaf drop), or for particular sub-regions are possible with this dataset as is. Comparing phenophase changes to each other can also aid researchers in targeting priority areas of exploration for both general and species interaction phenology studies. First Leaf Date had more advanced phenology for many species than FFD. All of the top 12 highest sample-size species advanced FLD more than 13 days in the contemporary time period, where only 4 of the 12 highest sample-size species for FFD advanced more than 13 days in the contemporary time period. First flower Date had slightly better representation by hardiness zone and was found to have variable differences in rate of advancement per hardiness zone. This variability in individual species response is an area for further questioning.

Climate modeling and spatial-temporal trends

We also plan to use these climate and phenology data to extend the spring index (a model of spring phenology of lilacs and many native understory shrubs) back in time (Ault et al. 2015, Schwartz 1998,) Currently the extent of spring index is limited by climate data, which is not widely available prior to 1900. We plan to explore broad-scale patterns in how all of the species in both datasets (regardless of overlap) are responding to changes in climate using new climate model approaches, extended Spring Indices and novel spatial analysis techniques. Our current study was focused on change in species over time and required a massive reduction to both the historic and contemporary datasets in order to attain matched species pairs. The combined modern and historic datasets in their entirety contain over 900 different species and will allow for deeper spatial-temporal exploration than found in the present study. With the larger dataset will also have the capacity to explore in more detail differences in community-level changes in particular locations—e.g., how are community shifts in phenology near Albany changing relative to those of New York City or the Great Lakes area, for example. This will help us further take advantage of the spatial extent of our data set and examine questions of community-level changes and changes in ecological relationships that cannot be addressed with other data sets.

Herbarium specimens:

The use of herbarium specimens is a validated approach to comparing phenological change across time. Data collection from herbarium records can have a large temporal and spatial range (Primack & Gallinat 2017) and past studies have used herbarium records to show changes in plant phenology (Thackeray et al. 2016, Spellman & Mulder 2016, Munson & Long 2017). For example, Thackeray et al. (2016) used herbarium specimens from 1960-2012 and compared them against local temperature and precipitation data, with plant phenophases averaging 4.3 days earlier per degree Celsius. Munson & Long (2016) used over 27,000 herbarium records of grass species across the western US to look at reproductive phenology of grass as it relates to temperature and

precipitation from 1895-2013. Their results suggest that climate change will have unequal effects across the western USA due to divergence in phenological responses among grass functional types, species, and eco-regions. Davis et al (2015) found that earliest flowering date estimated from herbarium records dependably reflected field observations of first flowering date and substantially increased the sampling range across climatic conditions. Spellman & Mulder (2016) used a combination of herbarium records and citizen science network observations to validate their findings. They found that their models were valid for understanding the relative shifts in the phenology of the focal species across a large geographic area but needed further calibration to provide accurate predictions for specific dates and locations. Our dataset may have the capability to provide ground-validated calibration and incorporate herbarium records to fill in the missing years and locations. There are many historic organizations in New York that have herbarium records which have not been fully evaluated for phenological study (e.g. New York Botanical Garden, Brooklyn Botanical Garden). Prior evaluation is recommended, as herbarium specimens were not originally collected to identify phenological events. Moreover, bias for collection time, full flowering specimens, and collection location can be a concern (Davis et al 2015).

Expanding the spatial and temporal range of this dataset:
Understanding phenological responses to climate change is of such ecological and evolutionary importance that it warrants increased efforts to collect long-term phenological data via new projects and searches of historical records (Miller-Rushing & Primack 2008). We currently know of some locations in New York where relatively long-term modern records (10-20 years) from individual naturalists exist in the same general locations as some of the historic sites. In addition to analyzing these site-specific datasets, searches for other datasets to extend the temporal and spatial capacity of this dataset will add to its research utility. We also plan to continue to aid in the expansion of the modern NYPP dataset by adding new locations and creating resources to support new and existing sites to increase observer retention, accuracy and community-level participation thereby increasing the volume and quality of species observations over time.

Exploration of phenology networks:
Historic datasets available for phenological comparison are usually from a single observer, a naturalist or nature enthusiast such as Henry David Thoreau or Thomas Jefferson (Miller-Rushing & Primack 2008), a line of generational observers such as Robert Marsham, Richard Fitter, Daniel Smiley (Cook et al. 2012) or are culturally or economically significant records for a species in a nation such as 1600 year-old cherry blossom records from Japan (Aono & Kazui 2008) and 630 year old grape harvest records from France (Chuine et al. 2004). We know of no other example of an organized historical network of phenology observers that can be compared to a contemporary network functioning in a similar fashion. An exploration into how these networks operated (past and present), which locations or organizations flourished or failed and what common circumstances contributed to success (or lack thereof) can yield valuable information on how to scale and sustain long-term monitoring networks

Appendix C.4 - First Flower Date and First Leaf Date for 37 different species.

Appendix Table C.4.1 **First Flower Date for 31 species.** All species were analyzed first pooled and then isolated by hardiness zones five, six, and seven (zone 4 removed due to low sample size and/or uneven distribution between time periods). Dashed lines indicate zones without adequate representation for comparison (n<3per time period per hardiness zone). Significant p-values reported in bold and orange.

First Flower Date	**All**	**All**	**Zone 5**	**Zone 6**	**Zone 7**
Species	Difference/ p-value	t/N	Difference/ p-value	Difference/ p-value	Difference/ p- value
Acer rubrum	14.90±2.03 **<.0001**	7.36 (300, 104)	18.93±3.28 **<.0001**	7.16±3.47 **0.0419**	11.06±4.06 **0.0072**
Acer saccharinum	14.11±10.13 0.1800	1.39 (9, 9)	---	---	-5.40±13.12 0.6948
Acer saccharum	11.51±2.09 **<.0001**	5.52 (83, 53)	8.14±2.42 **0.0015**	9.45±3.26 **0.0060**	18.29±10.29 0.0850
Achillea millefolium	-18.83±6.18 **0.0055**	-3.05 (5, 16)	---	-20.27±8.01 **0.0231**	---
Aquilegia canadensis	-8.89±7.28 0.2287	-1.22 (4, 39)	-9.96±6.02 0.1323	---	---
Asclepias syriaca	12.95±6.03 **0.0352**	2.15 (58, 17)	14.40±3.39 **0.0010**	1.32±4.65 0.7776	---
Caltha palustris	8.40±3.73 **0.0304**	2.56 (7, 30)	8.94±5.48 0.1264	---	---
Carpinus caroliana	10.00±14.27 0.4967	0.70 (11, 3)	---	---	---
Cornus florida	13.59±3.02 **<.0001**	4.49 (95, 37)	16.97±8.11 **0.0269**	6.85±4.35 0.1210	19.50±4.28 **<.0001**
Cornus sericea		-0.50	---	---	---

	-4.87±9.78 0.6248	(13, 6)			
Erythronium americanum	6.76±2.06 **0.0015**	3.28 (51, 47)	4.07±2.40 0.1003	2.50±2.74 0.3681	12.63±7.76 0.1220
Fagus grandifolia	13.59±8.86 0.1294	1.53 (75, 4)	---	---	---
Fragaria virginiana	4.41±4.70 0.3566	0.94 (23, 5)	---	---	---
Gleditsia triacanthos	37.55±3.76 **<.0001**	9.98 (9, 14)	---	---	43.33±3.02 **<.0001**
Kalmia latifolia	15.06±6.65 **0.0378**	2.26 (15, 7)	19.50±3.77 **0.0021**	-10.67±3.73 **0.0458**	---
Lindera benzoin	11.73±3.52 **0.0011**	3.33 (134, 18)	7.72±8.94 0.3961	7.37±3.02 **0.0185**	29.17±10.50 **0.0070**
Liriodendron tulipifera	27.50±5.03 **<.0001**	5.47 (116, 20)	22.08±7.59 **0.0115**	18.03±4.65 **0.0008**	25.36±11.79 **0.0341**
Maianthemum canadense	6.18±3.09 **0.0492**	2.00 (60, 14)	0.67±4.62 0.8873	---	-2.92±6.14 0.6474
Podophyllum peltatum	1.23±2.49 0.6240	0.49 (22, 13)	---	---	---
Populus tremuloides	1.93±4.51 0.6714	0.43 (23, 21)	---	---	---
Prunus serotina	3.14±±4.03 0.4369	0.78 (115, 12)	7.67±6.24 0.2292	---	-2.62±6.77 0.6995
Querus alba	11.41±4.38 **0.0116**	2.60 (52, 11)	13.83±8.36 0.1100	5.00±12.28 0.6960	17.08±7.78 **0.0379**

Sanguinaria canadensis	4.67±3.28 0.1589	1.43 (11, 54)	7.38±4.48 0.1103	---	---
Sassafras albidum	10.22±4.78 **0.0435**	2.14 (20, 5)	---	---	---
Syringa vulgaris	11.22±1.83 **<.0001**	6.14 (46, 49)	14.38±2.60 **<.0001**	8.88±2.67 **0.0024**	14.89±6.31 **0.0346**
Taraxacum officinale	7.21±2.77 **0.0101**	2.60 (30, 179)	7.31±4.93 0.1429	0.53±3.73 0.8881	12.68±4.65 **0.0092**
Tilia americana	11.28±9.82 0.2605	1.25 (5, 23)	-0.67±7.37 0.9290	---	---
Trientalis borealis	9.27±3.59 **0.0218**	2.58 (10, 6)	---	---	---
Trillium erectum	11.98±4.42 **0.0106**	2.71 (22, 13)	---	---	---
Ulmus americana	14.53±4.27 **0.0011**	3.40 (19, 48)	25.33±7.53 **0.0051**	---	13.06±7.44 0.0929
Viburnum acerifolium	30.00±6.79 **0.0013**	4.42 (6, 6)	---	---	---

Appendix Table C.4.2 **First Leaf Date for 19 species.** All species were analyzed first pooled and then isolated by hardiness zones five, six, and seven (zone 4 removed due to low sample size and/or uneven distribution between time periods). Dashed lines indicate zones without adequate representation for comparison (n<3per time period per hardiness zone). Significant p-values reported in bold orange.

First Leaf Date	All		Zone 5	Zone 6	Zone 7
Species	Difference/ p-value	t/N	Difference/ p-value	Difference/ p-value	Difference/ p-value
Acer rubrum	14.12±3.48 **<.0001**	4.05 (349, 19)	10.55±6.80 0.1241	13.75±4.12 **0.0011**	---
Acer saccharum	13.56±2.41 **<.0001**	5.62 (236, 29)	13.30±3.14 **<.0001**	11.53±4.03 **0.0054**	15.55±6.71 **0.0237**
Carya tomentosa	22.67±5.37 **<.0009**	4.22 (4, 12)	---	---	14.17±8.35 0.1505
Cercis canadensis	26.75±7.16 **0.0013**	3.74 (19, 4)	---	22.25±7.69 **0.0340**	---
Cornus florida	22.33±5.01 **<.0001**	4.45 (127, 14)	13.26±6.93 0.0765	30.69±9.51 **0.0020**	16.16±5.09 **0.0025**
Fraxinus americana	14.08±6.15 **0.0239**	2.29 (102, 8)	--- 0.2734	31.88±13.41 **0.0262**	16.52±8.02 **0.0438**
Gleditsia triacanthos	29.58±5.98 **0.0002**	4.95 (12, 4)	---	---	25.08±11.53 **0.0261**
Lindera benzoin	27.11±9.45 **0.0046**	2.87 (183, 4)	18.90±16.62 0.2642	25.66±14.29 **0.0388**	31.11±18.09 **0.0445**
Liriodendron tulipifera	25.95±4.20 **<.0001**	6.18 (128, 14)	---	21.19±4.29 **<.0001**	24.40±6.69 **0.0004**
Platanus occidentalis	20.11±7.88 **0.0241**	2.55 (8, 7)	---	---	17.25±14.65 0.2727

Populus tremuloides	11.77±6.28 **0.0355**	1.87 (26, 4)	11.33±5.78 **0.0338**	---	---
Prunus serotina	13.75±4.41 **0.0021**	3.12 (168, 10)	20.17±3.97 **<.0001**	---	-2.62±6.77 0.6995
Prunus virginiana	33.14±7.73 **0.0027**	4.29 (3, 7)	---	---	---
Querus alba	28.08±12.34 **0.0263**	2.28 (81, 18)	22.71±3.97 **<.0001**	10.31±3.33 **0.0074**	23.71±5.60 **0.0001**
Robinia pseudoacacia	12.88±5.70 **0.0328**	2.26 (3, 24)	---	10.03±6.54 0.1531	---
Sassafras albidum	15.78±10.51 0.1399	1.50 (46, 3)	---	---	19.96±12.21 0.1102
Syringa vulgaris	13.57±3.88 **0.0007**	3.50 (71, 28)	25.08±5.22 **<.0001**	20.00±4.54 **0.0001**	10.76±8.12 0.2214
Tilia americana	13.21±2.76 **<.0001**	4.79 (15, 20)	18.24±4.27 **0.0007**	11.70±3.80 **0.0068**	6.36±6.62 0.3690
Ulmus americana	18.34±3.95 **<.0001**	4.65 (20, 21)	22.80±10.74 **0.0389**	---	15.27±6.37 **0.0269**